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Antecedents of Pregnancy Among Women Marines

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ABSTRACT

Nine hundred fifty-six women Marines participated in a prospective study of the antecedents of pregnancy. The results indicated that attitudes toward pregnancy assessed during recruit training and contraceptive behavior prior to entry into the Marine Corps predict pregnancy. The study also revealed that the pregnancy rate among first term women Marines is significantly higher than that for other women the same age.

Antecedents of Pregnancy Among Women Marines

Becoming an effective contraceptor requires that a woman negotiate a complex sequence of psychological and behavioral events including: (a) becoming aware of the high risk of pregnancy when intercourse is unprotected, (b) obtaining adequate information about contraception, (c) acquiring the contraceptive devices and/or knowledge necessary to prevent pregnancy, and (d) using those devices and/or information consistently and effectively.[1,2] Many young women fail to negotiate these steps successfully. In fact, it is estimated that 24 percent of 18 year old women, and 44 percent of 20 year old women have experienced at least one pregnancy.[3] Numerous studies have indicated that most of these pregnancies are unintended.[3,4,5*]

Antecedents of Unplanned Pregnancy

In spite of the fact that birth control information and effective contraceptive methods are available to most young women in the United States, substantial numbers of sexually active women use unreliable methods of contraception (e.g., rhythm, withdrawal) or use no method at all. Research on the antecedents of unplanned pregnancy indicates that stress, anxiety and major life transitions are associated with irregular or ineffective contraception. More specifically, Miller[6] suggests that women are particularly susceptible to de-

creased contraceptive vigilance when they move away from their nuclear families and/or enter new environments. He hypothesizes that these kinds of situations may deplete a woman's psychological energy and detract from her ability to be continuously vigilant in avoiding conception. It is not surprising then, that confusion about career goals is also associated with ineffective use of contraceptives which lead to unplanned pregnancy.[7]

One of the most reliable findings regarding psychological antecedents of unplanned pregnancy is that ineffective contraception is inhibited by a negative orientation toward sex. This predisposition results in conservative or conflicted attitudes towards sex and discomfort with the decision to have sexual intercourse.[1,8] Women with these negative attitudes (called erotophobia or sex guilt) tend to have difficulty engaging in rational decision making about contraception. For example, sex guilt and erotophobia have been associated with: (a) lack of knowledge about sex and contraception;[9] (b) avoiding information about birth control;[9] (c) inconsistent and irrational attitudes and beliefs about birth control;[10] (d) choosing ineffective methods of contraception;[11–14] and (e) inconsistent use of chosen birth control methods.[12–14] These relationships are very reliable, but they have been demonstrated primarily on college student samples.

One purpose of the current study was to examine the antecedents of unplanned pregnancy in a non-student sample of women who are at relatively high risk of unplanned pregnancy because of their frequency of sexual intercourse and use of ineffective contraceptives. More specifically, the current study was designed to examine the antecedents of unplanned pregnancy in first term women Marines.

Women Marines

The preceding research on the situational and psychological antecedents of unplanned pregnancy suggests that first term women Marines may be particularly at risk—they are sexually active, have just completed a very stressful course in recruit training, are isolated from family and friends, and are likely to be experiencing uncertainty about their career goals and their relationships with men.

A series of studies conducted at the Naval Personnel Research and Development Center in San Diego in the early 1980s investigated attitudes, characteristics, and behaviors relevant to pregnancy and pregnancy attrition among first term women Marines. In the first of these studies, Royle[15] examined the relation between background variables, experience in the Marine Corps, and attrition among 1,271 recruits who entered the Marine Corps between 1976

and 1980. Her data revealed that women who attrite (both for pregnancy and for other reasons) have fewer "masculine" interests (e.g., sports) than pregnant women who remain in the Corps.

The second in this series of studies compared the backgrounds and Marine Corps experiences of first term women Marines who attrite and those who do not attrite.[16] This survey of 142 women revealed that women Marines in general have a relatively traditional orientation regarding having a family, and they plan to combine motherhood with their careers. However, those with the most traditional family orientations adapted least well to Marine Corps life—they were less satisfied and less well-adjusted than those with a less traditional orientation toward motherhood, suggesting that they would be most likely to attrite because of pregnancy.

In an extension of this research, Gerrard and Royle[17] examined traditional sex role orientation, feelings of isolation, and dissatisfaction with the Marine Corps as possible predictors of both pregnancy and pregnancy attrition in 610 first term enlisted women Marines. We found that both pregnancy and pregnancy attrition were predicted by the traditional orientation identified in the earlier two studies. Whether a woman left the service once she was pregnant, was also determined in large part by her commitment to family vs. career. In addition, we found that dissatisfaction with the Marine Corps did not discriminate between non-pregnant women, pregnant women who remained in the Corps, and women who had a pregnancy-related attrition. This latter finding suggests that dissatisfaction with the Marine Corps was not related to becoming pregnant.

A fourth study in this series[18] assessed first term Marines' sexual and contraceptive behaviors relevant to planned pregnancy. It revealed that many women (and men) had not adequately protected themselves from planned pregnancy prior to recruit training—10 percent of the women reported using no method of birth control the last time they had intercourse, and another 11 percent reported using relatively ineffective methods (withdrawal and rhythm). In addition, 16 percent of the women reported that they had experienced at least one pregnancy prior to recruit training.

It is important to note that with the exception of 196 of the 1,271 women in Royle[15] study, the women in all four of these studies were surveyed after recruit training. Thus, these studies did not investigate prediction of pregnancy from the women's attitudes in recruit training or sexual and contraceptive behaviors prior to recruit training.

Estimating pregnancy rates. The two previous studies that were designed to predict pregnancy and pregnancy attrition[15,17] both employed a limited classification system for pregnancy. In Royle,[15] a woman was classified as pregnant

if Marine records indicated that she left the Corps because she was pregnant, or indicated that she added an infant dependent between completion of recruit training and completion of her enlistment. The second study[17] added self-reported pregnancy, but only if the woman was pregnant at the time of the survey. Thus, both studies failed to identify any women who became pregnant after recruit training but did not deliver, either because of miscarriage or abortion (unless in the latter study the women were pregnant at the time of the survey). Likewise, women who got pregnant but left the Marine Corps for reasons other than pregnancy were classified as non-pregnant in both studies.

Two facts suggest that these methods of identifying pregnancies result in an underestimation of the pregnancy rate among first term women Marines. The first is pilot data on the sexual activity and contraceptive use of women Marines reported in Gerrard and Royle.[17] Estimates based on these data suggest that the actual pregnancy rate is significantly higher than the 6 percent to 16 pregnancy rates derived from the official records.[15] The second is data suggesting that abortions are common among women in the military. Hoiberg[19] reports that approximately 10 percent of Navy women received abortions in Navy hospitals each year between 1973 and 1975, and that for every 100 women in the Navy who got pregnant and left the service, there were an additional 60 to 80 women who got pregnant, but chose to end the pregnancy by abortion. Hoiberg's data were collected between 15 and 18 years ago at a time when abortions were being performed in Navy hospitals. Therefore, it is not appropriate to extrapolate from these data to estimate current abortion or pregnancy rates. It is, however, reasonable to assume that a significant proportion of women in the military still have abortions rather than carry their pregnancies to term, and aborted pregnancies have not been included in previous studies of pregnancy among women Marines.

Overview

The purpose of the current study was twofold. First it was designed to examine the relationships between erotophobia, sexual behavior, contraceptive effectiveness and pregnancy in a non-student sample. And second, it was designed to extend the findings of the previous series of studies of women Marines by examining the attitudinal and behavioral antecedents of pregnancy among first term women Marines. Specifically, this study was designed to determine whether women Marines' attitudes during recruit training and their sexual and contraceptive behavior prior to entering the Marine Corps predict pregnancy during the first term of enlistment.

Method

Subjects

The participants were 956 women Marines who completed recruit training between November 1986 and September 1987. All of the women were high school graduates, and 23 percent had some college. Six hundred and twenty-eight (66%) of the women were white, 208 (22%) were black, and 65 (7%) were Hispanic. The mean age of the women was 19.5, and 91 percent were single, 6 percent married and 3 percent divorced or separated.

Procedure

The first author asked for volunteers from 10 randomly selected recruit training classes at the Women's Battalion at the Parris Island Marine Corps Recruit Training Depot between November 1986 and August 1987. Because of the possibility that women in Marine Corps recruit training would feel coerced even if they were told that their participation was voluntary, potential participants were assured that there would be no adverse consequences associated with either skipping questions that they considered too personal, or not completing the questionnaire. No military personnel other than the recruits were present during the data collection sessions, and no military personnel were aware of which potential participants completed either the initial questionnaire or the follow-up questionnaires. Ninety-eight percent of the potential participants agreed to participate in the study and completed the initial questionnaire.

The initial survey was administered in a classroom setting in groups ranging in size from 66 to 112 within 2 weeks prior to graduation from recruit training. Follow-up surveys were mailed to each woman at her duty station 6, 12, and 18 months after their graduation.

Measures

Sexual Opinion Survey. This 21 item instrument (SOS) was developed by White, Fisher, Byrne and Kingma[20] to measure emotional reactions to sexuality (erotophobia/erotophilia). It assesses reactions to a variety of sexual activities on a seven point scale (e.g., "Masturbation can be exciting," "I do not enjoy day dreaming about sexual matters.") The SOS is related to affective responses to erotica and to approach/avoidance reactions to a variety of sex-related topics (for a review[21]). It has also been shown to be related to contraceptive knowledge, and use of effective contraceptive methods.[9,11–14,21–24] The scale is unrelated to social desirability.[20]

Sexual and contraceptive history. This instrument is an adaptation of questionnaires used by Royle, Molof, Winchell, and Gerrard,[18] and Geis and Gerrard[11] to collect contraceptive and sexual histories from college students and women Marines. It asks the woman to describe her sexual history and contraceptive behavior in detail:

> Starting with your first sexual partner, indicate *all* the periods of time you were sexually active. For each [period] indicate the frequency of intercourse, and the method of birth control you and your partner used. . . . Please start with the first man *you* had sexual intercourse with and work forward. . . . Be sure to include *all* periods of sexual activity even if you did not use any method of birth control.

Attitudes about pregnancy. Because the women's attitudes about getting pregnant were considered to be very important, we assessed these attitudes in a variety of ways. We inquired about whether the women planned to ever have children, and if so, how many they would like to have and at what age they would like to start their families. In addition, we had the women estimate the likelihood that they would experience a pregnancy in the 12 months following recruit training, indicate how inconvenient they thought it would be if they were to get pregnant in the 12 months following recruit training, and indicate how unhappy they would be if they were to become pregnant during that 12 months.

Birth control opinion questionnaire. This instrument was designed specifically for this study to measure attitudes toward, and biases against specific birth control methods. It assesses the women's perceptions of the effectiveness of specific methods (on a 7 point scale from 1 = "extremely effective", to 7 = "not at all effective"), and the woman's intentions to use the methods in the future (also on a 7 point scale).

Birth control knowledge. Birth control knowledge was assessed using a 23 item multiple choice instrument adapted from the knowledge test used by Royle et al.[18,24,25] This test is designed to assess information useful in avoiding unplanned pregnancy rather than biological or technical information about conception and contraception. The internal consistency of this instrument was acceptable (alpha coefficient = .77).

Follow-up Surveys

The follow-up surveys (at 6, 12, and 18 months) were mailed to participants at their duty stations. A second questionnaire was sent to women who failed to return a follow-up questionnaire within four weeks after it was mailed. If the questionnaire was returned "addressee unknown," or "moved, left no

forwarding address," the address was confirmed with Marine Corps Headquarters, and a second copy was mailed. If the second mailing also resulted in the return of the questionnaire by the post office or mail service at the woman's last duty station, the woman was counted as "unreachable" for that follow-up. This procedure resulted in three possible sources of attrition from the study: (1) failure to locate women for follow-up; (2) participant failure to respond; and (3) attrition from the Marine Corps.

Response rate. The response rate (responders/(initial participants - unreachable participants - attrites) for the six month follow-up was 46 percent, at the 12 month follow-up was 38 percent, and at the 18 month follow-up was 30 percent. Responders and nonresponders were not significantly different in terms of age, education, IQ, ethnic background, sexual and contraceptive attitudes or behaviors prior to recruit training, or initial attitudes toward motherhood.

Indicators of Pregnancy

A woman was classified as pregnant in the current study in three ways: The official record of pregnancy attrition provided by Headquarters U.S. Marine Corps, indication on Marine Corps records that the woman had added an infant dependent between completion of recruit training and the end of the study, and self-report of pregnancy since recruit training on follow-up questionnaires.

Results

Sexual and Contraceptive Experience Prior to Recruit Training

As a group the women entered recruit training with a significant amount of sexual experience (see Table 1). Eighty-five percent had engaged in sexual intercourse prior to joining the Marine Corps, with the nonvirgins reporting an average of 5.7 sexual partners. The sexually experienced women reported having intercourse an average of 8.9 times per month in the 3 months immediately prior to recruit training.**

At the initial survey administration, the women were asked to indicate which method(s) of birth control they *usually* used prior of recruit training and which method(s) they used the *last* time they had intercourse. Fifty-five percent of the nonvirgins reported using relatively effective methods (i.e., oral contraceptive or condoms) the last time that they had intercourse. Fifteen percent reported using less effective methods (i.e., rhythm or withdrawal), and 19

Table 1.—Sexual Activity and Contraceptive Use Prior to Recruit Training

Had prior sexual experience	85.0	
Frequency of intercourse[a]	8.9	
Number of partners[b]	5.7	
	Method Used at Last Intercourse	**Method Usually Used**
Oral contraceptives	39%	46%
Condom	16	15
Rhythm	6	5
Withdrawal	10	6
None	19	14

[a]Average frequency of intercourse per month over the 3 months prior to recruit training.
[b]Total number of partners prior to recruit training.

percent reported using no method of birth control the last time that they had intercourse (see Table 1).

Assuming that the birth control method a woman reports using the last time she engaged in intercourse is a good predictor of her future contraceptive use, and that her previous frequency of intercourse is a good predictor of her future frequency, it is possible to compute a projected pregnancy rate for the sample. The formula for this computation is

$$\sum_{i=1}^{m} [P_i \, FR_i \, Fq_i + C] \, (P)$$

where P_i = proportion of women using method i
FR_i = typical failure rate for method i
fq_i = adjusted frequency of intercourse for women using method i
C = correction factor for missing data
P = proportion of women who are sexually active

Using this formula, we projected that between 21 and 25 percent of the women in this sample would get pregnant in the first year of their enlistment.*** Twenty-one percent is a conservative estimate based on the assumption that women who were virgins during recruit training would not get pregnant in the first year after recruit training. Twenty-five percent is the estimate based on the assumption that these women would become sexually active, and that their frequency of intercourse and contraceptive use would be comparable to that of the women who were sexually experienced prior to recruit training (i.e., deleting P from the computation).

Relationship Between Attitudes Toward Sex and Sexual and Contraceptive Behavior

Attitudes toward sex do predict sexual activity in the women Marines—erotophobic women Marines (the top one-half of the SOS distribution) were almost twice as likely as erotophilic women Marines (the botton one-half of the SOS distribution) to be virgins entering recruit training (19.2% vs. 10.0%; $z = 4.53$, $p < .01$). The sexually active erotophobic women also reported fewer sexual partners than did the sexually active erotophilic women (4.3 vs. 7.3; $t(688) = 5.70$, $p < .001$), and less frequent intercourse (7.9 times per month vs. 10.2 times per month; $t(706) = 3.44$, $p < .01$).**** Comparison of the erotophobic and erotophilic women's contraceptive use, however, revealed no significant differences in these groups' use of contraceptives (all $ps > .90$).

Attitudes toward Pregnancy During Recruit Training

During recruit training, 92 percent of the women reported that they planned to have children at some time in the future, with the average number of children planned being 2.4. The average age that they planned to have their first child was 24.9. The mean response to the question "How inconvenient would it be for you to get pregnant in the next year?" was 6.2 (on a scale where 7 = extremely inconvenient). Their answers to the question "How unhappy would you be if you were to become pregnant in the next year?", clearly demonstrated that a sizable proportion of the women were ambivalent about the possibility of a pregnancy ($m = 4.7$ on a 7 point scale where 7 = "extremely unhappy").

Actual Pregnancy Rate

A simple additive computation of the pregnancy rate indicates that 25 percent of the women would get pregnant during the first 12 months following recruit training. This computation assumes that the rate at 12 months is the sum of the number of self-reported pregnancies, plus the number of pregnancy related attritions between 0 and 6 months, plus the number of self-reported pregnancies, pregnancy related attritions, and new infant dependents between 6 and 12 months. A more conservative calculation (the number of women reporting pregnancies)/(the total number of women who returned questionnaires at the 6 month and 12 month follow-up) results in an estimate of 18.2 percent.

Sixty percent of the women who conceived in the first 18 months after recruit training reported that they intended to carry their pregnancies to term

and keep their babies. Twelve percent reported miscarriages and 19 percent reported induced abortion. The remaining 9 percent were still pregnant and undecided about their plans at the time of the survey.

Antecedents of Pregnancy

A series of exploratory multivariate analyses of variance was conducted to identify attitudes and behaviors that could be used to predict which women Marines became pregnant during the first 18 months after recruit training. These analyses revealed that women who became pregnant were significantly different at recruit training from those who avoided pregnancy on a number of variables. These variables can be characterized along two dimensions: (1) the attitudes about pregnancy the women held during recruit training, and (2) their attitudes about contraception and their contraceptive behavior prior to enlistment. Measures of these attitudes and behaviors were entered into a discriminant function analysis which confirmed that they reliably predict which women became pregnant (X^2 (df = 9) = 33.10, $p < .01$; see Table 2).

Attitudes toward pregnancy. Women Marines who became pregnant had more positive attitudes toward pregnancy during recruit training than did women Marines who did not become pregnant. More specifically, during

Table 2.—Differences Between Pregnant and Non-Pregnant Women Marines

Discriminant Function Analysis X^2 (df = 9) = 33.10, $p < .01$

Univariate Tests

Variable	Pregnant	Nonpregnant	Wilks' Lambda *F*
Perceived convenience of pregnancy (in next 12 months)[a]	5.91	6.14	.908*
Plans to get pregnant in next 3 years[b]	4.61	5.42	.928*
Estimated likelihood of pregnancy (in next 12 months)[c]	20.65	10.73	.960*
Typical failure rate of method of birth control used at last intercourse[d]	30.91	22.53	.946*
Knowledge of birth control[e]	18.66	19.12	.936*
Opinion of rhythm and withdrawal[f]	10.77	10.85	.912*
Intention to use rhythm and withdrawal[g]	10.67	11.39	.922*
Previous pregnancy[h]	1.63	1.75	.929*

[a]Rating scale ranges from 1 "not at all inconvenient" to 7 = "extremely inconvenient."
[b]Rating scale ranges from 1 = "definitely plan to get pregnant" to 7 = "definitely do not plan to get pregnant."
[c]Rating scale ranges from 0 to 100.
[d]Scale ranges from 0 to 100 with numbers indicating the typical likelihood of pregnancy over 12 months.
[e]Scale ranges from 0–40; high scores indicate more knowledge.
[f]Scale ranges from 2 = "extremely effective" to 14 = "extremely ineffective."
[g]Scale ranges from 2 = "would definitely use" to 14 = "definitely would not use."
[h]Scale ranges from 1 to 2 with higher numbers indicating greater proportions have had a previous pregnancy.
*$p < .01$

recruit training, women who later became pregnant were significantly more likely to report that they thought that a pregnancy within the next 12 months would not be inconvenient (5.91 vs. 6.14 on a 7 point scale ranging from 1 = "not at all inconvenient" to 7 = "extremely inconvenient"; Wilks' Lambda $F = .91$, $p < .01$). Women who became pregnant were also more likely to report that they were planning to get pregnant in the next 3 years (4.61 vs. 5.42 on a 7 point scale where 1 = "definitely plan to get pregnant" and 7 = "definitely do not plan to get pregnant"; Wilks' Lambda $F = .93$, $p < .01$), and were more likely than other recruits to report that they were likely to get pregnant during the coming year (20.7 vs. 10.8 on a 100 point scale, $p < .01$). Women who conceived during the first year after recruit training were less likely to have previously experienced a pregnancy than those who did not (Wilks' Lambda = .929, $p < .01$).

Contraceptive behavior prior to entering recruit training. Pregnant women Marines were more likely to have a history of unprotected intercourse and/or inadequate contraceptive protection prior to recruit training than were the women who did not get pregnant. The typical failure rate of the method birth control the pregnant women used prior to recruit training was 30.9 percent failure, as compared to 22.5 for the women who did not get pregnant (Wilks' Lambda = .95, $p < .01$). Consistent with this history, the women who became pregnant were less knowledgeable about contraception, more likely to rate rhythm and withdrawal as effective methods of birth control, and more likely to report intentions to use rhythm, and withdrawal (both Wilks' Lambdas > .90, both $ps < .01$).

Discussion

Perhaps the most striking result from the current study is that the pregnancy rate for first term women Marines is significantly higher than the rate for other women of the same age—18 to 25 percent of this sample got pregnant in the first year after recruit training versus a 10 to 11 percent pregnancy rate per year for the general population.[3,28] In addition, pregnant women in the current sample were significantly more likely to carry their pregnancies to term and keep their babies than are other pregnant women their age (the abortion rate for pregnant women age 18–24 is typically about 40%[3,29] compared to the 20% reported in this sample). These differences between women Marines and the general population are consistent with the fact that women Marines are more family oriented and are likely to be planning to have children at an earlier age and than are other women their age.[26]

There are a number of possible explanations for these differences between women Marines and other women. One is that the Marine Corps attracts more traditional (family oriented) women. These women then, are more likely to have children. Another possibility is that the first term of service in the Marine Corps presents women with opportunities conducive to sexual activity, (e.g., they are outnumbered by men approximately 20 to 1),[30] or that women in the masculine environment of the Marine Corps feel pressure to prove their femininity, and this pressure leads them to become involved in risky sexual relationships that lead to pregnancy. Yet another possibility is that the stress and major life change involved in entering the Marine Corps leads to either less contraceptive vigilance or decreased motivation to avoid pregnancy.[6,7]

Predicting Pregnancy

The variables that discriminate between those women Marines who get pregnant and those who did not suggest that, in large part, differences in knowledge, attitudes and behavior patterns that the women bring with them into the Marine Corps are responsible for the relatively high pregnancy rate among these women. That is, the best predictors of pregnancy in the first 18 months of service are lack of knowledge about birth control, positive attitudes toward pregnancy reported during recruit training, and ineffective contraceptive behaviors practiced prior to recruit training. This does not rule out the possibility that women Marines are less vigilant with their contraception after undergoing the stress of recruit training, or that these women engage in riskier sexual behaviors because of situational pressures. It is clear however, that women Marines have more traditional attitudes and are more family oriented than most women their age even *before* they leave recruit training to work in a male dominated environment, and that these attitudes are associated with pregnancy.

Planned vs. Unplanned Pregnancy

Any discussion of pregnancy in the Marine Corps would be incomplete without mention of the possibility that women Marines who become pregnant do so intentionally. The current data do indicate that some women Marine's pregnancies are planned, some are accidental, and some are the result of ambivalence about pregnancy or emotional conflict about their sexual behavior. It is impossible, however, to determine what percent of the women fall into each of these three categories. It is clear though, that the majority of pregnancies among first term women Marines fit the definition of unplanned pregnancy—they are pregnancies which were not intended at the time of

conception. In other words, ambivalence about pregnancy may inhibit women from taking steps 3 and 4 outlined in the introduction, and thus result in some pregnancies that were not intended, but were not entirely unwanted.

Erotophobia and Sexual and Contraceptive Behavior

Although the SOS scores of the women in this study predicted their sexual activity, the current data fail to replicate the previously reported association between negative attitudes toward sex and use of ineffective methods of contraception. More specifically, the erotophobic women Marines were not less effective contraceptors than were the erotophilic women Marines. Two differences between this sample of women Marines and the college student samples used in previous studies could be responsible for this difference. One is that this sample is significantly more sexually experienced than college students, both in terms of their total number of partners and in terms of their frequency of intercourse.[28] The other difference is that this sample of Marine women had more experience with a variety of contraceptive methods than have college women.[26] These differences between samples raise the possibility that attitudes toward sex are predictive of contraceptive use only in less sexually and contraceptively experienced samples, like college students. Regardless of the reason for the failure to replicate, however, these data suggest caution in generalizing from research on college students' contraceptive behavior to other samples.

Actual Pregnancy Rate

In spite of the relatively high pregnancy rate in this sample, one must entertain the possibility that the current study has underestimated the actual pregnancy rate among women Marines. Although the current study represents an improvement in identifying pregnancies, our classification system was not perfect. That is, there are three ways in which the current study could have misclassified a pregnant women as non-pregnant. First, a woman in the current study would have been classified as non-pregnant if she was pregnant but left from the Marine Corps for reasons other than pregnancy. Second, a woman who delivered a baby would not have been classified as pregnant if the baby were not listed as her dependent but rather was listed as her husband's dependent. And third, we must consider the possibility that discomfort or unhappiness about a pregnancy could have led some women to fail to respond to the follow-up questionnaires. All of these factors raise the possibility that the actual pregnancy rate among women Marines is higher than the 18 to 25 percent estimate the current data suggest.

Summary

In general, first term women Marines enter the Marine Corps with relatively high levels of sexual experience and relatively ineffective contraceptive habits. These attitudes and behaviors combine with the women's positive attitudes toward pregnancy and motherhood to result in approximately one-fourth of the women getting pregnant during the first year following recruit training.

Notes

*An unplanned pregnancy is defined as a pregnancy that was unintended at the time of conception.

**The women Marines in this study were significantly more sexually active than a comparison sample of over 300 freshmen women from 3 large universities.[26] More specifically, only 66% of the college women were nonvirgins, and the sexually active college women reported an average of 3.9 sexual partners and engaging in intercourse an average of 6.0 times per month.

***Typical failure rates for specific methods of birth control are the percent of women that would be expected to get pregnant over the course of one year using the method.[27] These failure rates include both pregnancies due to method failure and pregnancies due to failure to use the method correctly and consistently.

****Different *n*s for different analyses are the result of incomplete data.

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The Discovery of Oscillatory Electric Current

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ABSTRACT

The history of the discovery of electric oscillation is reviewed.

I. Introduction

After Oersted's discovery in 1820, of a magnetic influence from a galvanic circuit, the two separate phenomena of electricity and of magnetism were tied together to form the new science of electromagnetism. The next evolutionary advance taken, was the discovery in 1826 by Felix Savary of Paris, of oscillatory currents produced by a discharge. His discovery was reasoned from experimental observation of the magnetic periodicity of fine steel needles, when they became magnetized as a consequence of the discharge current of the Leyden jar.

During the period of years from 1835 until 1842, Joseph Henry of the College of New Jersey at Princeton (later to become Princeton University) developed his theories on the nature of the discharge current. For the purposes of this paper, only those of his discharge studies that were concerned with his conceptualization of the phenomenon of electric oscillation are considered. Prof. Henry's 1842 experiments concerning the oscillatory nature of the discharge current, were completed with his knowledge of the previous work of Savary, whom he mentions. But Henry's experiments were masterpieces of applications of self-made equipment, not only to prove the existence of oscillatory currents discharging from the Leyden jar, but also to show the existence of oscillatory currents for various induction at a distance setups, as well as for what he called "dynamic induction" at a distance from lightning.

Karl Wilhelm Knochenhauer postulated a theory in 1842, for the existence

of electric oscillations in an electrically stressed aether impregnating what we now call the dielectric medium of the condenser (i.e., capacitor). This electrical stressing of the aether in the glass, was a consequence, he thought, of the charging of the Leyden jar. In 1847, Hermann Ludwig Ferdinand Helmholtz derived the oscillation of electric discharge currents from the principle of the conservation of energy.

2. Studies by Felix Savary on Magnetic Periodicity, and His Subsequent Deduction of the Existence of Oscillatory Current

Discharge currents produced in the early 19th century, were those from the Leyden jar, or the magic tableau (tablet) which is also known as the Franklin square. This is a device consisting of a sheet of glass dielectric that is sandwiched in between two sheets of foil, and this may also have been called a battery. Another source for a discharge current was the cascade or succession of sparks that were thrown from the prime conductor of a hand cranked friction machine. The 18th century version of this machine uses a belt to obtain a high rate of rotation, generally of a glass disk or glass sphere that is held against a leather "rubber". This type of machine was invented by Francis Hawksbee in 1709. Today, such a machine would be called an electrostatic generator or an electron pump. Later 19th century machines of this type include the Holtz and the Wimshurst generators. Other than this, the magneto-electric generator was in use, such as the Saxton machine invented by the American Joseph Saxton of Philadelphia and London, or the Pixii machine.

I begin with the discharge studies of Felix Savary (born in 1797 and died in 1841) who was Professor of Astronomy and Geodesy at the École Polytechnique of Paris. What then was the intellectual source for Prof. Savary's investigation of the magnetism that is developed from the discharge circuit, and how was he led to the distinction between a discharge current and a voltaic current whose source was the pile of Volta? He and de Monferrand (called Demonferrand by James Cumming[1] of the same period, who was President of the Cambridge Philosophical Society and professor of chemistry at Cambridge University; see ref. 2) had published a study to demonstrate Coulomb's laws of force for electric currents in closed voltaic circuits, and a new application of the formula of Ampère to represent the mutual action of two infinitely small portions of the electric current. Self-induction and mutual induction were but an evolutionary step removed from the study of the mutual actions of the magnetism of one or two circuits. Because this study by Savary and de Monferrand is a side issue in this history, it is not placed in the reference section, and for those readers who find such things of interest, it suffices to

say that their study was read at the Academy of Sciences meeting of 3 February 1823, and published in vol. 22 (1823) pp. 259–264, of the Bibliothèque universelle (LC: Q2.A77).

But these studies by Savary and de Monferrand answer only a part of the question regarding the intellectual source of Savary's inquiry into the nature of the discharge current. The other part of the question seems to be answerable from Savary's comments about a new series of experiments that were carried out by Leopoldo Nobili (born in 1784 and died in Florence in August of 1835). According to the remarks translated from French[16] in Savary's paper:

> [pages 8–9]
> "Since the researches of Mr. Arago, Mr. Nobili has published on some interesting magnetization experiments. One of these consists in making an examination, of either the electric discharge, or the current of the pile (Mr. Nobili has never separated these two means of magnetization), with a plane spiral of copper wire. If between the spires [which are] insulated one from the other[,] one fixes, perpendicularly to its plane, some needles of steel, one finds that the needles situated towards the center and adjacent to the circumference are magnetized in contrary senses; [and] that by consequence at a certain distance from the center the magnetization is null."

We can recognize a number of ideas from this paragraph. Firstly, note that Nobili at that time failed to distinguish between the current of the discharge (which today we recognize as a.c.) and the current of the pile (which today we recognize as d.c.). Secondly, and this is most important, Savary saw in Nobili's experiment, the contrary senses of magnetism imparted to the steel needle depending upon its position with regard to the center of the spiral and the circumference of the spiral; implying that the magnetism of a needle can change polarity depending upon where it is situated in distance at various positions on the wire spiral. This idea can be regarded as the most important source of these investigations by Savary which led him to his discovery of the oscillatory nature of the discharge current.

Consider now, his experiments. They are summarized in Table I.

Nobili's above-mentioned study of the influence of the position of the needle fixed perpendicularly to the flat coil, on the polarity of magnetism after the discharge current has passed, I believe, is the germinal ideal in Savary's research on oscillatory current. The following question and reply were made by Savary.[16] The reply is a statement of his theory which came from his experiments.

> [pages 54–56]
> "is the movement of electricity during the discharge, composed, to the contrary, of a suite of oscillations, transmitted from the wire to the surrounding medium, and soon amortisized by the resistances which increase rapidly with the absolute velocity of the agitated particles?"

Table 1.—Experiments reported by F. Savary in his 1827 paper

1. Rectilinear wire experiments (using different lengths of platinum wire) to detect periodicity of magnetism due to the discharge current. (He used needles 5mm, 10mm, and 15mm in length.)
2. Experiments to study the mutual influence of the different parts of the discharge circuit (using a brass wire 1 meter in length).
3. Experiment to determine if the force of magnetization of a discharge can be modified by resistance. (The concept of impedance was unknown.)
   (a) Savary discussed the production of high temperatures in the platinum wire during the discharge.
   (b) He studied whether tempering of the steel needles affected the outcome of the magnetization.
   (c) He described the sense and intensity of the magnetization of the steel needles.
4. Experiment to study the influence of the hardness of the needles on their magnetization.
5. Experiment to study the influence of the diameter of the needles on their magnetization.
6. Experiments to detect periodicity of magnetism on steel needles using a brass wire helix wound on a hollow wooden cylinder 9cm long, about 6.5mm in diameter. He discussed:
   (a) the quantity of electric fluid in a Leyden bottle;
   (b) the experiment of Arago in which two helices were used, wound in the same sense and placed one within the other;
   (c) an experiment where two helices were wound in opposite senses and placed one within the other;
   (d) the effects from systems consisting of 3 or 4 helices enclosed one in the other and turning alternatively in opposite senses.
7. Experiment to magnetize 3 needles placed together in the same helix using the same discharge. The needles were respectively 5mm, 10mm, and 15mm in length.
8. Experiments in reduction or augmentation of magnetism by the use of copper, silver, and of tin sheathing, of needles placed in the helix.

NOTE. Savary mentioned that in order to eliminate the effect of terrestrial magnetism, one always places the needles during the discharge in a direction perpendicular to the magnetic meridian.

> "All the phenomena conduce this hypothesis, which in fact depends, not only on intensity, but the sense of magnetism following the laws by which small movements are amortisized in the wire, in the medium which surrounds it, [and] in the substance which receives and conserves the magnetization."
>
> . . . . "An oscillating pendulum in an atmosphere . . . is an example of this genre of movement."

So, therefore, Savary's findings can be summarized for their comparison with the similar experiments conducted by J. Henry. Thus:

(a) the needles are made to oscillate in time (dynamical phenomenon);

(b) each needle possesses a sense of magnetization whatever is the distance of the needle to the nearby wire;

(c) "an electric discharge is a phenomenon of movement." there are alternatives of opposite magnetisms that are observed at diverse distances from a conductor;

(d) "the electric movement during the discharge is composed . . . of a [train] of oscillations transmitted from the wire . . . to the surrounding environs [which] soon dies . . . ."; and,

(e) the oscillations have a finite amplitude.

The 1826 studies by Savary on the oscillatory nature of the discharge current were also analyzed a year later by Gerrit Moll of the Netherlands, and were mentioned elsewhere at that time, as science news items.[17,18]

3. The Researches of Joseph Henry Concerning the Oscillatory Nature of the Leyden Jar Discharge

In 1835, Joseph Henry[6] propounded a theory concerning his observations of changes in the sense of magnetization (i.e., changes in polarity) and changes in the amplitudes of magnetization of steel needles that were exposed to the action of the discharge current. I think that this theory is but an evolutionary step to what I call his mature theory of 1842 on the subject of oscillation. A summary of his findings is made in Table II.

Table II.—Henry's 1835 experimental discoveries published in "Contributions, No. II"

(a) the direction of the magnetic polarity of the needles varies with their distance from the wire
(b) this action of inducing magnetic polarity is periodical
(c) hypothesis of an induced secondary current oppositely directed in the region of the wire; and then a tertiary at a yet greater distance, oppositely directed to the secondary current, etc.

(a) and (b) are the same statements as given by Savary in 1826-7. Hypothesis (c) describes a dynamical notion occurring in time, which implies the existence of higher order but weaker currents at greater distances from the discharge wire. This could be considered as a rough equivalence for an alternating electromagnetic field.

In 1838, Henry published his "Contributions, No. III".[7] A synopsis of his findings about discharge current appears in Table III.

Table III.—Henry's 1838 experiments results on the magnetism of discharge currents and currents induced from sparks from the prime conductor of a generator

(a′) the direction of the magnetic polarity due to the secondary current, varies with its distance from the primary circuit
(b′) the action of inducing magnetic polarity from the secondary circuit is periodical
(c′) the intensity of the induction decreases with increasing distance from the wire

Other than studying magnetic periodicity due to the secondary current, this 1838 study adds nothing essentially new to the 1835 study. In Henry's 1842 publication[10] "Contributions, No. V", he explicitly mentions that an electric discharge is alternating (oscillating), and he proposes the mechanical mechanism of a Franklin fluid. Helmholtz on the other hand, in his independent discovery of the oscillatory character of a discharge (in 1847) which he derived from the principle of the conservation of energy applied to electricity, did not attempt to provide any such mechanism, but he did provide a mathematical foundation for his theory. At that time, the Weber-Fechner theory had just been proposed in 1845–6, which exerted influence on Helmholtz's researches into his application of the concept of the conservation of energy to electricity.

It was left to William Thomson (later Lord Kelvin) in England, to provide a mathematical theory to describe electric oscillation in 1853.

In articles 113–134 of his 1838 publication,[7] Henry described experiments demonstrating oscillatory characteristics of the discharge current. From these experiments he showed 1, the discovery of a difference in the direction of galvanic (d.c.) currents and ordinary (a.c.) currents of the different orders; and 2, he conceived the idea that the direction of the currents might depend on the distance of the conductors. This latter idea is theoretically the same as that which was proposed by Henry in 1835. Henry noted in article 116:[7]

> "When a discharge from the half gallon jar was passed through one of these [narrow strips of tinfoil], an induced current in the same direction was obtained from the other. The ribands were then sep[a]rated, by plates of glass, to the distance of 1/20th of an inch; the current was still in the same direction, or plus. When the distance was increased to about 1/8th of an inch, no induced current could be obtained; and when they were still further sep[a]rated the current again appeared, but was now *found to have a different direction, or to be minus*. No other change was observed in the direction of the current; the intensity of the induction decreased as the ribands were sep[a]rated. The existence and direction of the current, in this experiment, were determined by the polarity of the needle in the spiral attached to the ends of the ribands."
>
> Art, 134. ". . . the facts here presented . . . appear to be intimately connected with various phenomena, which have been known for some years, but which have not been referred to any general law of action. Of this class are the discoveries of Savary, on the alternate magnetism of steel needles, placed at different distances from the line of a discharge of ordinary electricity. . . ."

Compare the above statement from 1838 with his statement of Feb. 1835, found in Henry's publication[6] "Contributions . . . No. II . . . ."

> "When a current is transmitted through a wire, and a number of small needles are placed transverse to it, but at different distances, the direction of the magnetic polarity of the needles varies with their distance from the conducting wire. The action is also periodical; diminishing as the distance increases, until it becomes zero; the polarity of the needles is then inverted, acquires a maximum, decreases to zero again, and then resumes the first polarity; several alterations of this kind being observed. Now this is precisely what would take place if we suppose that the principle current induces a secondary one in an opposite direction in the air surrounding the conductor, and this again another in an opposite direction at a great distance, and so on. The needles at different distances would be acted on by the different currents, and thus the phenomena described would be produced."

Henry seems to have applied to the notion of electric oscillation, a mechanistic fluid conception. The notion of electric fluids with hydrodynamical properties had already been conceived of at an earlier date. Ben Franklin

proposed a single electric fluid in contradistinction to a two-fluid theory. Objections to Franklin's theory were overcome by an ad hoc hypothesis provided by Franz Ulrich Theodor (Theodosius) AEpinus in his book *Tentamen theoria electricitatis et magnetismi* [*"An Essay on the theory of electricity and magnetism"*]". His book was published in the year 1759 by the Imperial Academy of St. Petersburg.

It is important to remember that Henry developed this hypothesis in relation to the dielectric wall of the condenser, and had probably reasoned that the alternating current flow could explain the open circuit of the conduction current interrupted by the non-conducting wall of the condenser. Maxwell had not yet developed his own notion of the displacement current $\partial_t \mathbf{D}$ which allowed the closure of the conduction current through the wall of the condenser.

Henry's laboratory notes[8,9] of June 1st and 2nd of 1842, document the progression of his magnetization experiments which led to his 1842 publication.[10] The principal new finding reported in this 1842 paper, with regard to the oscillation of the discharge current, stemmed from "a new examination of the phenomena of the change in direction of the induced currents, with a change in distance, etc." This went a step beyond Savary's discoveries, in that Henry introduced the concept that oscillation can be induced by the process of induction, to occur in currents of higher orders, however feeble they might be. This is the basic notion of the working principle of the transformer device.

4. The Researches of Helmholtz and of Knochenhauer on Electric Oscillation

In the year 1847, there appeared in print an extensive treatise by Hermann Helmholtz,[5] a physician and physicist, in which he described his theory of the conservation of energy. In one section, he described the energy equivalent of the electrical processes, and one can see how heat energy and electrical energy have an intimate connection, both being but modes of energy. Thus:

> [page 33]
> *"The energy equivalent of the electrical processes"*
>
> ⋮
>
> "Riess *) has shown through experiments, that" . . . [in the circuit of the discharge current, he] "developed heat proportional to the value Q/S. With S he designates only the surface area of the coating of the [Leyden] flask . . . . Out of his experiments has Vorsselmann de Heer **) furthermore followed, as like Knochenhauer***) on his own, that the development of heat from the same charge of the same battery remains the same . . ."

"It is easy to explain this law, as soon as we imagine to ourselves the discharging of a battery not as a one way movement of the electricity in one direction, but as a back and forth fluctuation of itself between the both coatings, in oscillation, which becomes ever smaller, until the entire kinetic energy itself is annihilated through the sum of the resistances."

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*) "Poggd. Ann. XLIII 47."
**) "Poggd. Ann. XLVIII 292. See there the observation of Riess. Especially p. 320."
***) "Ann. LXII 364. LXIV 64."

On page 32 of his 1842–3 paper,[11] K. W. Knochenhauer mentioned his conception of electric oscillations in a stressed aether. He was in agreement with the views of Michael Faraday on the nature of the dielectric, except that Knochenhauer developed a view in which an electric aether impregnated the dielectric material of the condenser, as well as the space surrounding it. He stated that (English translation from German):

". . . I will call this the electric stress of the aether. This will arise through the continued charging, and comes finally to such a degree, that the non-conductor can not further resist its congestion, and the electric oscillation of the stressed aether follows. For namely nothing other than as a singular oscillation, whose kind and manner is yet to be found, do I consider to be the spark."

He placed a great emphasis on the study of the electric spark. From the above remarks, it is evident that he believed an oscillation was transmitted by means of a stressed electric aether. His concept preceded the researches of J. C. Maxwell on the electromagnetic theory of light, by 21 years. These remarks by Knochenhauer on oscillation were made in 1842, the same year in which Prof. Henry published his mature theory on the oscillation of the discharge current, on the other side of the Atlantic Ocean. But Prof. Henry considered these oscillating currents as oscillations of a hydrodynamical electric fluid. He did not consider the properties of such a fluid, as to whether it was viscous or ideal, compressible or incompressible; but merely assumed its existence.

In Europe, a number of researchers began to come to grips with the theory of electric oscillation in the decade of the 1840s. Amongst the European researchers, H. W. Dove[3] mentioned the researches of both Savary and Henry. And W. G. Hankel[4] discussed Savary's 1826–7 researches with the magnetization of needles. Hankel discussed Ampère's theory of magnetism, whose hypothesis concerning magnetism he supported, and he discussed Dove's 1841 paper in opposition to it. And he also mentioned the work of Marianini, Henry, and Riess.

Peter Theophil Riess, was familiar with the researches of Henry.[14,15] However, in 1840, he did not accept the theory of electric oscillation, in this, the early part of his career. This can be seen from his remarks, which I have translated from his 19th latinic German.[13]

> "How impermissible is the conclusion of an anomalous magnetization being dependent on the change in the current direction, relative to Savary's experiments, that it depends on the mass and the hardness of the magnetized needle, one must therefore declare about the secondary current, that it is at this or every distance [from the primary] changing its direction, according as the one or the other needle itself is employed in the proof."

This shows that Savary's theory of electric oscillation was not universally accepted by 1840.

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Identification of a Superforce in the Einstein Field Equations

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ABSTRACT

The Einstein field equations provide the underlying principles to theories of gravitation, the big bang, black holes, and cosmology in general. Many variants of these equations have been developed by Einstein and subsequent investigators. These variants include differences in mathematical form, components, arithmetic signs, and the presence of particular constants, and corresponding mathematical solutions. The objective of this paper is to examine the variants of the Einstein field equations where the combination of fundamental constants c^4/G occurs. This combination of the speed of light, c, and the universal gravitational constant, G, has the units of force. Significant relationships of this force to the Planck mass, Planck length, cosmic numbers, color force between quarks, and the Einstein field equations are derived and discussed. The characteristics of c^4/G fulfill predictions for the superforce.

Introduction

The Einstein field equations are the starting point for theories of the big bang, black holes, superstrings, and cosmology in general. A brief description will be given of the Einstein field equations. Then, it will be shown how an extremely strong force, that fulfills the predictions of a superforce, is contained in the Einstein field equations. This force has been overlooked since nothing is added to or taken away from the Einstein field equations. The properties of the superforce will be explained. Important quantities which are contained in various cosmological theories will be related to the superforce. The resulting relationships will be used to suggest a different approach to the big bang.

Two points will be emphasized over and over again. One point is that the Einstein field equations will be taken just as Einstein proposed them. The other point is that the results presented here fulfill predictions made by several physicists. Starting with the same equations analyzed by others, the outcome is predictable, but not exactly in the way that would be normally expected.

The Einstein Field Equations and Their Interpretation

Albert Einstein published[1] an extensive description of his general theory of relativity in 1916. Over the next few years, he published other papers that presented variants on this theory. Subsequent to Einstein, others also published additional variations on the general theory of relativity, all based upon the same formulations by Einstein. There have been so many different variations that C. Misner[2] and others list 37 accepted forms of the Einstein field equations that define the foundation to the general theory of relativity that represents our most advanced understanding of the theory of gravitation.

Einstein[3] proposed that the formulation of one of his field equations of gravitation be stated as follows:

$$T_{\mu\nu} = \kappa(R_{\mu\nu} - 1/2 g_{\mu\nu} R) \tag{1}$$

He defined the terms in this equation in another publication.[4] In equation (1),

- $R_{\mu\nu}$ denotes the contracted Riemann tensor of curvature,
- R represents the scalar of curvature formed by repeated contraction,
- $T_{\mu\nu}$ is the energy-tensor of "matter",
- $g_{\mu\nu}$ is the fundamental tensor, and
- κ is a constant.

Einstein loosely used κ as a constant that had several different magnitudes and units. It is defined in inverted form on page 160 of the 1917 publication

as $\kappa^{-1} = 8\,\pi\,G/c^2$, where G is Newton's universal constant of gravitation and c is the speed of light.

At the time that Einstein proposed equation (1), physical observations indicated that the universe was spatially finite. On the other hand, equation (1) predicts an expanding universe. To correct this problem, he decided that

> "on the left-hand side of [the] field equation . . . we may add the fundamental tensor $g_{\mu\nu}$, multiplied by a universal constant, $-\lambda$,"

so that

$$T_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa(R_{\mu\nu} - 1/2g_{\mu\nu}R) \tag{2}$$

The constant, λ, has since come to be called the "cosmological constant." The insertion of the cosmological constant assures that equation (2) is a model of a spatially finite universe.

Let us rearrange equation (2), to put it in one of the more currently expressed forms

$$R_{\mu\nu} - 1/2g_{\mu\nu}R + \wedge g_{\mu\nu} = kT_{\mu\nu} \tag{3}$$

In this case $\wedge = -\lambda/\kappa$ and $k = -1/\kappa$. Equation (3), with and without the cosmological constant, will be the focus of the remainder of this paper.

It is important to note the dimensional units used in equation (3). Each of the groups of components are in units of cm^{-2}. The reason for these units is that the Einstein field equations are only considered valid for a small volume of space. The actual units, in cgs form, of each group of components is cm/cm^3, or length per unit volume. Specifically, $R_{\mu\nu}$, R, and $\wedge$ are in these units. The fundamental tensor is dimensionless. The right side of equation (3) has a more complicated structure. In fact, Einstein[5] is reputed to have said that the components of the right hand side were a blemish in his theory because they are essentially non-geometrical entities.

Different dimensional units may be used to define $T_{\mu\nu}$ and k. When $T_{\mu\nu}$ is expressed as energy per unit volume, k is l/force. When $T_{\mu\nu}$ is a mass per unit volume, or density, k has units of cm/gr. Should $T_{\mu\nu}$ be a momentum per unit volume, k assumes sec/gr units.

The units of k in equation (3) are particularly important for the case when $T_{\mu\nu}$ is expressed as an energy per unit volume. Under these conditions, $k = 8\,\pi\,G/c^4$. It would appear from the various solutions of equation (3) that the $8\,\pi$ and the G/c^4 components are from different sources. The combination of fundamental constants G/c^4, or rather the inverse, c^4/G, is of particular interest. The speed of light to the fourth power divided by Newton's universal gravitational constant, c^4/G, has the units of force. The magnitude of this

force, referred to as F_S, is enormous: $F_S = 1.2 \times 10^{49}$ dynes. If F_S existed in nature, it would be superstrong. Compelling reasons dictate that F_S be called the superforce. Attention will be focused on this superforce and its unusual characteristics for the remainder of this paper.

Superforce

P. Davies published[6] a book in 1984 called "Superforce: The Search for a Grand Unified Theory of Nature." He makes the following statements in this book:

> ". . . investigations point toward a compelling idea, that all nature is ultimately controlled by the activities of a single *superforce*. . . .The search for a superforce can be traced to the early work of Einstein and others, . . ."

The major premise of this paper is that c^4/G is this superforce. It is contained in the Einstein field equations and was overlooked by him and everyone else. The probable reasons for this oversight will be explained. Several derivations will be performed to justify calling c^4/G the superforce.

Combinations of fundamental constants[7] which repeatedly turn up in cosmological theories are the:

$$\text{Planck mass,} \quad m_p = (hc/2\pi G)^{1/2} \tag{4}$$

$$\text{Planck length,} \quad r_p = (hG/2\pi c^3)^{1/2} \tag{5}$$

$$\text{Planck time,} \quad t_p = (hG/2\pi c^5)^{1/2} \tag{6}$$

The Planck mass is considered to be the largest possible particle mass, $m_p = 2.2 \times 10^{-5}$ gr. The Planck length, $r_p = 1.6 \times 10^{-33}$ cm, is a measure of the failure of the vacuum and may be the minimum size black hole. The Planck time, $t_p = 5.4 \times 10^{-44}$ sec, is the time it takes light to travel the Planck length. Many theories of the origin of the universe go back to the Planck time. The Planck length is involved in more theories than the other Planck terms. According to C. Isham,[8] it is a

> "fundamental length in nature. . . , and it is at this scale that we might expect to see some effects of quantum gravity . . . . it has long been assumed that something rather odd will happen as . . . matter passes through the Planck length. . . ."

The Planck length, mass, and time are all associated through mathematical approximations[9] to several measurements of the universe. These measure-

ments include: the solar mass; main-sequence lifetime of stars; the Hawking evaporation rate for black holes; maximum allowable size for a planet; and, age, mass, and density of the universe.

A straightforward explanation may be given as to why the Planck functions turn up so frequently in astrophysical and cosmological theories. If two Planck masses are assumed to interact over a range equal to the Planck length, the resulting Newtonian gravitational force is equal to the superforce.

$$m_p{}^2G/r_p^2 = c^4/G \tag{7}$$

It may be inferred from this interaction between two boundary limit relationships such as the Planck mass and the Planck length that F_S represents a limit of some sort. The superforce should also be related to the same phenomena that involves the Planck mass and the Planck length. Thus, according to Wagoner and Goldsmith,[7]

> "Therefore, for now we must regard the Planck barrier as another effective limit to our universe."

We cannot make calculations earlier than the Planck era. The reason why the Planck mass, Planck length and Planck time occur so frequently in cosmological theories is that they are indirectly contained in the Einstein field equations. Based upon equation (7), k in equation (3) is equal to $8\ \pi\ r_p^2/m_p{}^2G$ in energy units and $8\ \pi\ t_p^2/m_p{}^2G$ in mass units. The Planck conditions are easily introduced in this manner into the Einstein field equations.

There is a further link between the superforce and the Einstein field equations. A weak-field solution of the Einstein field equations leads to the prediction of gravitational waves. A rotating mass has a time-varying quadrapole moment that generates gravitational radiation with a gravitational luminosity, L. According to Douglas and Braginsky,[10]

> ". . . an upper limit on the luminosity of an astronomical source can be estimated . . ."

$$L_{ast} < c^5/G \approx 4 \times 10^{59} \text{ ergs/sec} \tag{8}$$

The limit to gravitational luminosity is the superforce times the speed of light, $F_S \cdot c$, which is equivalent to a maximum energy flow per unit time.

The relationships indicated by equations (7) and (8) have associated the superforce with limiting conditions for physical phenomena. The inference is that the superforce may also represent a limit. It will be assumed, for the sake of discussion, that F_S is the maximum possible force in the universe. If F_S

were the maximum possible force and m_p were the maximum possible particle mass, there should be a maximum acceleration, called the Planck acceleration, a_p, to go with the Planck mass, which is

$$a_p = F_S/m_p = (2\pi c^7/hG)^{1/2} \tag{9}$$

The magnitude of a_p, which is composed of fundamental constants, is 5.56×10^{53} cm/sec^2. The Planck acceleration is defined here for the first time.

One of the most often cited solutions to the Einstein field equations is the Schwartzschild limit, $r_s = 2mG/c^2$. This limit prescribes the event horizon of a non-rotating black hole where the gravitational strength of a collapsing body of matter is so strong that not even light can escape. There may be some exception[11] due to quantum effects which leads to Hawking radiation or Hawking evaporation. Nevertheless, there is a probable boundary to black holes defined by the Schwartzschild limit. There is a similar Newtonian gravitational collapse limit as a result of the superforce,

$$m^2G/r_N^2 = c^4/G \tag{10}$$

$$r_N = mG/c^2 \tag{11}$$

By comparison, $2r_N = r_s$. The gravitational collapse limit based upon Newtonian gravitation is half that of Einsteinian gravitation. This difference could be due to different mechanisms, the geometrical shape of the universe used in the Einstein field equations, or to some unknown reason. The similarities between r_N and r_s demand an explanation.

Before rejecting r_N in favor of r_s, it should be noted that the following relationship,

$$n = MG/Rc^2 \tag{12}$$

where M and R are the mass and radius of astrophysical bodies, is referred to by C. Will[12] as a

> "characteristic measure of the size of relativistic effects in bodies."

The value of n for the sun is 10^{-5}; for a white dwarf, it is 10^{-3}; and, it approaches 0.3 for a neutron star. There are no observations for $n > 1$ so that r_N may indeed have a physical significance.

If the Newtonian gravitational collapse limit defined by equation (11) is multiplied by c^2 on both sides and rearranged, the result is

$$E = mc^2 = F_S \cdot r_N \tag{13}$$

The relationship given by equation (13) would imply that r_N is indeed the gravitational collapse limit of matter. In other words, equations (11) and (13)

indicate that in a plot of the Newtonian gravitational force versus distance, the area under the curve at r_N and F_S is equal to the rest mass energy of the interacting entities. The inference from this observation is that the superforce, F_S, confines matter/energy in black holes.

Since the superforce is composed of two fundamental constants, its magnitude would be effected by any changes in the fundamental constants. It would require relatively large changes in the speed of light or the gravitational constant to produce a significant change in the superforce. The evolution of the universe would not have proceeded the way it has if there had been any major variations in the fundamental constants.[13] Consequently, it may be assumed that the magnitude of the superforce has remained constant over the age of the universe.

Another interesting set of numbers can be generated with the help of the superforce. The Coulomb force may be used to derive a series of functions similar to the Planck functions. By definition, the Coulomb force is equal to the superforce at a distance called the Coulomb length,

$$r_K = (e^2G/c^4)^{1/2} = 1.4 \times 10^{-34}\ \text{cm} \tag{14}$$

The time it takes for light to travel this distance is the Coulomb time,

$$t_K = (e^2G/c^6) = 4.6 \times 10^{-44}\ \text{sec} \tag{15}$$

The Coulomb mass is calculated when the gravitational collapse limit is equal to the Coulomb length,

$$m_K = (e^2/G)^{1/2} = 1.9 \times 10^{-6}\ \text{gr} \tag{16}$$

The Coulomb acceleration is calculated from $F_S = m_K a_K$, or

$$a_K = (c^8/e^2G)^{1/2} = 6.5 \times 10^{54}\ \text{cm/sec}^2 \tag{17}$$

Some of the Coulomb functions have been derived before, but not from the superforce. It is possible to derive each of these same Coulomb functions by multiplying the corresponding Planck function by the square root of the fine structure constant.

Cosmic Numbers

The role of the superforce in explaining various cosmic numbers further justifies the assertion that F_S is the largest possible force. Cosmic numbers are very large numbers that recur in cosmological theories for no known

physical reason. One of these cosmic numbers is the Eddington number[14],

$$N_E = h^2c^2/4\pi^2m^4G^2 \tag{18}$$

Sir Arthur Eddington was an outstanding astronomer who was a contemporary of Einstein. Eddington was one of the earliest proponents of the special and general theories of relativity. In the year 1919, he led the expedition[15] to Principe Isle in the Atlantic Ocean south of Nigeria to measure the Einstein prediction of the gravitational bending of light rays. As a result of a derivation based upon the Einstein field equations, Eddington derived N_E and noted that $N_E \approx 10^{80}$ for the mass of one of the mesons. Eddington thought that this number, in itself, was significant and even assumed that there were 10^{80} protons and 10^{80} electrons in the universe. The resulting mass was close to physical observations of the day. Eddington later changed his mind[16] about equation (18) when he said it was equal to $2 \times 136 \times 2^{256}$ and called this result the "cosmical number".

Recognition of the superforce, however, finally does allow a physical interpretation for the Eddington number as defined by equation (18). Consider the relative magnitude of the superforce, F_S, to that of the Newtonian gravitational force, F_G, at the Compton wavelength,

$$F_S/F_G = (hc/2\pi m^2G)^2 = N_E \tag{19}$$

In essence, the Eddington number is the relative strength of the largest force in the universe to the weakest force.

Another of the cosmic numbers, N_1, is given by

$$N_1 = (N_E)^{1/2} = hc/2\pi m^2G \tag{20}$$

The inverse of this cosmic number also corresponds to a representation of the gravitational coupling constant. In this case, the color force between quarks, F_c, could be defined in the following way relative to the superforce,

$$F_c = F_S/N_1 = 2\pi m^2c^3/h \tag{21}$$

The color force would have a theoretical magnitude of 7.1×10^{10} dynes for the mass of a proton. It just so happens that this is precisely the measured[17] magnitude of the color force at the Compton wavelength of a proton. The color force between quarks is bracketed between the superforce and the gravitational force. The superforce is 1.7×10^{38} times the color force between quarks. This should give validity to calling c^4/G the superforce.

Why did Einstein, and others, overlook the superforce in the Einstein field equations? There are three probable reasons. One of the reasons is the em-

phasis on spacetime and the curvature of space in equations (1), (2), and (3). Another reason has to do with the various forms of κ and k. The most likely reason is because of the assumption made by Einstein and almost every subsequent researcher using the Einstein field equations. Einstein assumed that the fundamental constants c and G were equal to one; $c = G = 1$. This assumption equates 1.2×10^{49} to 1 and wipes out the visible presence of the superforce.

Cosmological Model

If there were a superforce as predicted, and this force had a finite magnitude which could very well be the maximum possible force in the universe, then, the superforce could significantly impact theories about the origin of the universe. A particular cosmological model is suggested from the characteristics of the superforce.

There are two predominant theories of the origin of the universe, both based on the Einstein field equations. One approach is called the "standard big bang." In the beginning, all of the matter-energy of the universe was collapsed into a dimensionless point at infinite density and infinite force. This point at zero time is called a singularity because all of the laws of nature are unique at this point since the laws must be applicable to infinite conditions rather than the finite characteristics of the observable universe. Once the expansion of the big bang began, the normal laws of physics prevailed. Predictions for the singularity have been made back to the Planck time, or so-called Planck era. Many of the characteristics of the current universe can be predicted but there are difficulties with the smoothness and flatness problems.

To correct for the shortcomings of the standard big bang model, A. Guth[18] and others proposed an "inflationary big bang." In this model, the expansion of the universe takes place in two stages. The first stage is an extremely rapid expansion from a singularity until the Planck era. Then, the expansion proceeds the same as the big bang. This approach resolves many of the problems encountered with the standard big bang, but the inflationary big bang has its own problems. The primary problem is trying to explain events during the inflationary period up to the Planck time. It is necessary to define a false vacuum with negative pressure. There is also a vacuum energy density associated with the false vacuum. It is suggested that the reason that it is necessary to define a false vacuum is to hurdle the threshold posed by the superforce. In fact, the superforce enters into the definition of the vacuum energy density, u_{vac}, and the pressure of the vacuum, p_{vac}:

$$p_{vac} \equiv -u_{vac} = -\lambda c^4/8\pi G \qquad (22)$$

Equation (22) essentially nulls out the inflationary period at the superforce.

A third alternative to the standard big bang and the inflationary big bang is possible with identification of the superforce. The model is called the "finite big bang." All of the original matter-energy of the universe contracted to a finite gravitational collapse limit confined by the superforce. A valid solution for the Einstein field equations at the beginning of time is

$$R_{00} \times c^4/G = 4\pi T_{00} \tag{23}$$

In this case, all of the mass-energy of the universe, $4\pi T_{00}$, was contained in a region, R_{00}, and held together by the superforce, c^4/G. There is no need to resort to a singularity and all of the accompanying infinities. The universe began from a finite ball of mass-energy. At about 10^{-46} sec, the family of fermions was created with decay of the Coulomb masses in the original structure. At about 10^{-33} sec, the family of bosons was generated from decay of the pre-existent Planck masses. After 10^{-13} sec, the superforce decayed and the fundamental forces took control. The smoothness and flatness problems are particularly resolved by this approach.

Conclusions

The superforce was first identified by the author in 1976. Subsequent to the original derivation, several presentations were made and papers prepared[19] which included the superforce but did not emphasize it. This is the first such paper that addresses the superforce by itself. Based upon experience, it has been observed that there is a general reticence in endowing c^4/G with any significance. This reaction was understandable initially, but more and more evidence has been accumulated on the hidden role of c^4/G and its impact on the theoretical understanding of the universe.

Observations about c^4/G may be grouped into two categories: those which are mathematically and observationally correct and those that are more speculative. From a mathematical and dimensional perspective, there is no doubt that c^4/G has the units of force. This force has an enormous magnitude that is 1.7×10^{38} times stronger than the measured color force between quarks and the strong interaction between nucleons. Moreover, there is no doubt that c^4/G appears in inverse form in versions of the Einstein field equations. When Newton's universal law of gravitation is expressed in terms of the Planck mass and the Planck length, it is equal to c^4/G. Thus, both Newtonian and Planck conditions are present as an identity in the Einstein field equations.

A Planck acceleration may be defined using Newton's force law, the Planck mass, and c^4/G. Various combinations of fundamental constants may be defined using the Coulomb force and c^4/G that are related through the square root of the fine structure constant and the Planck mass, length, time, and acceleration, respectively. A physical explanation of the Eddington number, as well as other cosmic numbers, are possible with c^4/G. The gravitational coupling constant can be derived from this understanding of the Eddington number. The maximum possible gravitational luminosity is defined in terms of c^4/G. The false vacuum pressure and energy density are also based upon c^4/G. All of the statements about c^4/G in this paragraph may be backed up by mathematical expressions. Moreover, these comments are all valid without introducing the concept that c^4/G may be the superforce. The intent has been to identify those relationships where c^4/G plays a role either by its presence or as a bridge between other functions. It may be concluded that c^4/G is more than a fortuitous combination of the fundamental constants because of its ubiquitous roles in theoretical and observational physics.

From a speculative and judgmental viewpoint, it would appear that c^4/G deserves to be called the superforce. It is far stronger than any of the four fundamental forces and could satisfy the conditions for convergence of the four fundamental forces. Almost all solutions to the Einstein field equations could be interpreted differently based upon the presence of the superforce. The meaning of the cosmological constant, the conditions of the big bang, the structure of black holes, the unification of the four fundamental forces, and the concepts of strings and superstrings must all account for the role of the superforce.

The superforce is a combination of fundamental constants that surely must represent some boundary condition in nature. Apparently, there is more than one maximum boundary condition: maximum velocity, c; maximum particle mass, m_p; maximum gravitational luminosity, L; maximum force, F_S; and, maximum acceleration, a_p. Because of these maximum conditions, there may also be a minimum gravitational collapse limit. These boundary conditions suggest that there is no singularity as currently defined. The superforce provides an additional justification for what R. Matzner and his co-authors[20] state many physicists already believe,

> ". . .true singularities do not exist, . . ."

The big bang started from finite dimensions. Black holes terminate in finite dimensions. Nature is finite. Only the supernatural is infinite. All of these conditions are fulfilled by the superforce, c^4/G, which has always been present in the Einstein field equations.

Correspondence may be addressed to the author at the above address. This paper was presented on October 4, 1989, as a colloquium talk to the Physics Department of the Illinois Institute of Technology, Chicago, Illinois.

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Human-Computer Interaction: Psychological Perspectives

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The field of Human-Computer Interaction (HCI) has developed primarily during the last 15–20 years. Concern for HCI, however, was expressed much earlier by Mauchly in 1947 when discussing the ease of use of machine coding systems to program EDVAC he stated:

> "Any machine coding system should be judged quite largely from the point of view of how easy it is for the operator to obtain results." (Randell, 1973).

Hardware concerns such as the design of CRT screens and input devices dominated the early HCI efforts. More recently, interest has shifted toward principles of information presentation and ease-of-use concerns.

The introduction of the first time-shared interactive system in 1963, i.e., MAC, and the BASIC programming language stimulated interest in human factors problems of non-specialists users. The growth in power and speed and the reduction in size and cost of computers through the reduction in size of the switching unit from the transistor to large scale integration and very large scale integration has helped promote interest in human-computer interaction issues. Indeed, the development of the personal computer during the mid-1970's, which made low-cost computers with graphic displays available, provided an important impetus to the increased use of computers in psychological studies. Today, the field of HCI is a collaborative endeavor among computer scientists, human factors specialists, and psychologists.

The importance of the subject of Human-Computer Interaction has been recognized in the computing and information technology industry during the last few years. In the United States, the number of human factors specialists working in the HCI area is estimated to have increased four to five times

during the last decade. The ACM-SIGCHI Conference, first conducted in 1982, has become an annual event; and the attendance approaches 2000 persons. Recent surveys by the Human Factors Society and the Ergonomics Society indicate that about 50 percent of their membership are occasionally involved in the design and the evaluation of human-computer interfaces.

With this brief history in mind, the Executive Committee of the Applied Experimental and Engineering Psychologists, Division 21 of APA, agreed to sponsor a mid-year meeting with the Human Factors Society Potomac Chapter in Washington, DC, March 1–2, 1990, on the subject "Human-Computer Interaction: Psychological Perspectives." On March 1, 1990, David E. Kieras, University of Michigan, presented a tutorial, "An Overview of Human-Computer Interaction." On March 2, 1990, the following papers were presented at the Symposium: "Application of the Model Human Processor," Bonnie E. John, Carnegie-Mellon University; "The Effects of Rapid Prototyping on User Behavior in System Design," by David L. Sewell, Search Technology, and William B. Johnson, Galaxy Scientific Corporation; "Natural Language Interfaces," by Lance A. Miller, Science Applications International Corporation; "Knowledge Representations Used by Computer Programmers," by Scott P. Robertson, Rutgers University; "The Human Factors of Voice Interfaces," John C. Thomas, NYNEX; and "Advisory Materials for Computer Interfaces: Using Written and Animated Graphical Instructions," by Jay Elkerton, University of Michigan. Most of the papers from this symposium are presented in two special issues of the *Journal of the Washington Academy of Sciences*.

Reference

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An Overview of Human-Computer Interaction

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ABSTRACT

An overview is presented of the field of Human-Computer Interaction (HCI), with an emphasis on the topic of user interface design. The kinds of activity in HCI are summarized, and the relationships to the field of Human Factors and Computer Science are discussed. Two approaches to the user interface design problem are summarized: the standard human factors approach, and the newer theory-based engineering model approach. The basic concepts of user interface design within these two approaches are briefly described. Key references to the literature are included.

Introduction

An informal overview of Human-Computer Interaction (HCI) is provided. The overview has four parts: First, HCI, and its basic subject matter, user interface design, is defined with some discussion of its current importance. Second, HCI as a field of academic and industrial activity is described in terms of the participants and their orientations. Third, the two basic approaches to HCI and user interface design are described and compared; these are the standard Human Factors approach and the newer Engineering approach. The fourth section is a brief summary of some key principles and concepts from both approaches. The paper concludes with a brief statement about future goals for the HCI field.

What is Human-Computer Interaction?

Human-Computer Interaction (HCI) is a broad field. It includes the social impact of computers, the use of computers in education, and potentially everything else involving humans and computers. This is not a homogeneous field but a bewilderingly varied one; there is no universally held agreement on

research topics, goals, methodology, or a standard curriculum. But one shared belief is that improving human-computer system performance can be accomplished through better design of the user interface. Thus the main emphasis in HCI is *user interface design*.

User Interfaces

The *user interface* is that part of the system that the user directly interacts with; for example, it is the portion of the system that makes a PC different from a Macintosh from the user's point of view. The user interface involves the specific hardware features of the machine, such as the type of display and input devices, and the behavior of the software, which includes several aspects:

- The specific behavior of a particular application program.
- Conventions or user interface standards for a machine or system.
- The general environment supplied by the machine.
- The specific behavior of the operating system.
- The supporting documentation, training, and online help.

Where do User Interfaces Come From?

Most user interfaces are designed by programmers whose primary concern is functionality of the software. The software developer's intuition is the primary driver of the design, and serious use of human factors is the *exception,* rather than the rule. Bennett (1986) has pointed out that the manager of a software development effort is judged to succeed or fail depending on the *function* of the product, the *cost* of development, and the *schedule,* whether the product is shipped on time. The problem is that the manager of a development effort is normally not evaluated in terms of the usability of the product.

User interfaces are developed in three important settings which can be briefly described. The first is the mainframe system software, which is the kind of software that runs on large administrative systems, typically based on IBM hardware. Functionality is almost the exclusive concern for this software, and there is very little concern for usability. Because of the large initial expense of these systems and their software, there is almost no possibility for change, so users must adapt to the system, no matter how clumsy it is. Thus there is no market pressure for usability, and the users, typically secretarial and clerical personnel, are a captive audience. Under current standards of usability, these systems are often a nightmare, even though the tasks involved, such as ordering supplies, conceptually are far simpler than those the users routinely perform with high-end word processors on smaller machines.

Personal computer software is developed in two major settings. The first is

the larger companies that have prospered because one or more of their products has become a standard of its type. New releases of these products are becoming increasingly more complex, but because of the large market share, they are starting to suffer from the captive audience syndrome. Users have become so accustomed to these high functionality packages that the cost of switching to a different one has become high. Thus in some cases, even in the personal computer market where the usability of software is generally high, we are beginning to see the complex and confusing interfaces characteristic of mainframe system software.

However, in the second personal computer setting, software is developed in the context of small companies that are usually based on an entrepreneur or creative individual. Such products are based on an inspiration for new functionality or an especially good user interface for an old idea. A couple of examples can be given: Cricketgraph for the Macintosh does not really incorporate any new ideas about data graphing functionality, but it has become a best seller simply because this functionality is extremely well delivered, making graphs very easy to construct. ThinkTank, originally on the PC, is an example of an idea for a new type of functionality, namely the "outline processor." The user can construct and manipulate outlines, manipulating ideas with much more ease than paper and pencil or conventional word processors. ThinkTank first popularized this idea, and although it had a very clumsy user interface, it was still a very functional and important program. Its successor is the More II program on the Macintosh in which the functionality is coupled with a much more usable interface. Despite the success of personal computer software developed in small companies, the development process for the user interface is largely "seat of the pants", and the evaluation of the interface is primarily through user testing of early releases ("Beta Testing") and user comments and complaints.

Why HCI is Important Now

HCI is a "hot" topic now because personal computer technology has made everybody a user, and this mass market for software makes usability, as well as functionality, a selling point for software. But in addition, over the last few years the Macintosh interface has set a new standard for usability, in that many computer users now expect a consistent and highly usable set of application interfaces. These have flourished in the Macintosh software marketplace because of deliberate strategies on the part of Apple in the form of guidelines and system architecture than encourage applications to conform to the standard user interfaces.

The Future of Usability

But the future is by no means assured. Good user interface design can still not be taken for granted. The computer industry is still doing user interface design primarily by the seat of the pants: It is mostly intuitive, with very little systematic research or testing and evaluation. The consequences so far are that there have been many wasted opportunities for progress. For example, new systems, such as the Next computer, are not necessarily any better than existing systems and might even be worse. Also, the Macintosh has been on the market for several years now, but no real competitor has emerged. Instead, various myths and misunderstandings about usability have arisen, leading to pointless lawsuits over "look and feel", which are misguided because they miss the point of the Macintosh user interface. The widespread misunderstanding of the Macintosh-style *graphic user interface* (GUI), seems to have misled many computer industry experts into the belief that simply copying the superficial aspects of the Macintosh interface will automatically lead to a more usable system (see Elkerton and Palmiter, this conference). There are also some great potentials for disaster, such as the drive to make UNIX and some of its new GUIs a standard. No systematic research or testing has been done on these new interfaces, and UNIX is well known to be barely usable at all. The forces within the computer industry pushing for these standards could thus trap users for quite a few years into marginally usable systems. So progress is not assured by any means; it is quite possible that in the year 2000, people will be struggling with systems that are *less* usable than currently available.

What is the Relation Betwen HCI and Computer Science?

Computer science should include HCI, but generally does not, in spite of the fact that many conventional computer science concepts are actually based on human performance, and the limiting factor in computer system performance is often the human user. Three arguments will be given that HCI is a central part of computer science: First, many key concepts are psychologically-based. For example, because humans have a capacity for relatively fast input, but relatively slow central processing, and slow output, time-sharing makes sense; a shared computer system can rapidly transmit information to multiple user displays and then wait for individual users to eventually hit the keys on their keyboard. If human performance did not have this property, time sharing as we know it would not make sense. Other concepts, such as structured programming, or the widespread belief that user interfaces should involve a minimum number of keystrokes, are also based on beliefs about human per-

formance. A second argument is that most application programs consist mainly of user interface code, as contrasted with the code that actually does the computations in question. Thus, much of the software development cost is in the user interface. It only makes proper economic sense to insure that the design of the interface is good, so that the code will not have to be rewritten, and that there is some proportionality between the cost of the code and its impact on usage of the product. A third argument is that in modern computer systems, human performance is the basic bottleneck in the total system throughput. Computer scientists will worry themselves sick over squeezing every last fraction of MIPS out of computer hardware, but will think nothing of delivering a user interface that repeatedly stumps the user for seconds at a time. With modern technology, confusing the user for a second's time is the equivalent of throwing away millions of instructions. Computer scientists would never allow their hardware to be so radically inefficient, but they have not broadened their scope to include the throughput of the whole human-machine system.

Thus courses in human-computer interaction or user interface design are not common in computer science departments. Where they do exist, they tend to be viewed with some skepticism as being "soft" or "not really engineering." The field of HCI generally has a problem in that it has not established its credibility as a technical discipline with mainstream computer science. Within industry, computer specialists are usually not aware of HCI techniques or results, and often do not take usability seriously; they believe it is simply a matter of subjective opinion rather than a specifiable design goal like other aspects of the computer hardware and software.

What is the Relation Between HCI and Human Factors?

Likewise HCI should be a subset of Human Factors, but judging at least from the standard human factors textbooks and other sources, HCI is either ignored or given fairly low priority. For example, in the Sanders and McCormick (1987) textbook on human factors there is no index or table of contents entry for *computer;* the only related topics are cursor positioning devices, alphanumeric displays, and the physical ergonomic issues in VDT workstation design. Even the more psychologically-oriented Kantowitz and Sorkin (1983) textbook discusses computer systems only in the context of data entry systems and computer programming, which is a reasonable topic, but certainly not a mainstream one.

Interestingly enough, the Salvendy *Handbook of Human Factors* (1987) includes a substantial number of chapters on human factors in computer sys-

tems. The topics are ergonomic design of VDT workstations, software psychology, user interface design, input devices, speech I/O, text editors, and some other miscellaneous topics. Thus within Human Factors, HCI is only sometimes considered an important topic.

HCI People and Activities

One way to get a picture of the nature of work in HCI is to summarize the different kinds of people and activities in the field. This summary is somewhat flippant, but it will convey the overall flavor of the field. A more systematic and thorough description is a sociological task well beyond the scope of this presentation.

The Psychologists

Human factors stalwarts. Many human factors people are moving into HCI under the assumption that improving interface usability is just another human factors problem, and standard human factors approaches and techniques can solve it. But as will be argued more below, traditional human factors methods do not appear to be fast enough for the typical product development cycle, and the traditional strengths of human factors do not seem to be the main issues in computer usability.

Rapid evaluators and prototypers. This group is attempting to keep the standard human factors approach in the game by trying to develop better and faster ways to mock up and evaluate systems. They have had some notable successes, but the data collection process is still fairly slow and expensive. These methods require a great deal of understanding of behavioral data, and so they are not generally usable by the computer science professionals responsible for developing user interfaces. However, if the human factors specialist has control of the interface design, these methods appear to work very well.

Cognitive psychology strip miners. I have a certain affinity for this position because it is where my own interest in HCI started. This is a group of academic cognitive psychologists, who recognize that HCI is a good place to study some basic questions in cognitive psychology, such as how people acquire and use mental models or procedural knowledge. I am calling them "strip miners" here because the basic philosophy is to exploit the area by mining the useful results and then moving on to some other research domain. Thus this group does not have a basic commitment to improving user interfaces.

The problem for the cognitive psychology strip miners is that there is in fact nothing special about HCI situations from the basic research point of view. That is, the same basic research questions appear in a variety of other settings, such as the traditional control panel systems that are very common in human-machine interaction situations. In addition, HCI situations are in fact often very difficult to study. One must implement a simulation of a real piece of software, or instrument an existing piece of software, or use tedious videotape methods. All of these involve considerable time and expense, which is rarely repaid in basic scientific results.

Would-be cognitive engineers. This is the group that I currently place myself in. The concept of this group is that the HCI specialist should be able to do *engineering,* just like the rest of the design team. HCI engineering consists of constructing quantitative and predictive models of the HCI situation that can be used to evaluate user interface designs without empirical testing. The basic source of these models is current cognitive psychology results and theory. Despite some research successes, the problem for this approach is that it has not really been invented yet; there are no convincing demonstrations that the approach is useful in product design. In addition, the engineering approach to HCI seems to rub almost everybody else in the field the wrong way.

The Computer Scientists

Tool builders. This group is primarily interested in developing tools for building user interfaces; thus they are especially concerned with user interface management systems and prototyping tools, but they approach it from a computer science orientation. They are primarily interested in the *technology* of user interfaces rather than their usability. The concern that I have with this effort is that they may be merely developing efficient ways for software developers to continue building poor interfaces.

Artificial intelligence strip miners. Like the cognitive psychology strip miners, this group is interested in user interfaces only to the extent that this topic is useful for issues deemed important elsewhere. The argument advanced by this group is that an adequately intelligent computer would solve most usability problems; rather than making the user figure out the computer, the computer could figure out the user! There seems to be a belief among AI people that HCI is a good domain for building certain AI systems, and they often justify the considerable cost of AI systems with the usability benefits that would result. The latter is a weak argument, because industry in general

does not support user interface work enthusiastically; the AI-based approach to usability is thus an expensive way to be ignored, rather than a cheap way.

But there is a serious philosophical problem involved in this approach. It assumes that the computer would be most useful to humans functioning as a *collaborator* rather than as a *tool*. Thus the intelligent computer would present itself as basically human-like and will attempt to collaborate or cooperate with the user, instead of passively submitting to the user's will. Given that most people have trouble communicating with their secretaries, spouses, or professional colleagues, it seems foolish to want to have the same problems with one's computer, as opposed to simply telling it what to do.

Time will tell whether the computer-as-collaborator model for HCI is viable. In the meantime, most user interface work focuses on the computer-as-tool approach. This capitalizes on the apparent fact that most problems with computer system usability are relatively straightforward problems of bad design, and thus can be fixed in a relatively straightforward way. There is no need to use artificial intelligence to make systems usable; most of the problems can be handled simply by better design practices and techniques.

Visionaries and technology innovators. This group appears to believe that new ideas about user interface technology, or new computer functionality, will solve the problem of usability. While it is very clear that a single-minded emphasis on technology has produced many bad interfaces, and has impeded usability as often as it has helped, it is also clear that without these visionaries and innovators there would be no new technology to apply. The problem is that new technology seems to be applied to user interfaces routinely, without any thoughtful consideration about whether there will be any net benefit for the user. The result is a certain amount of wasted effort. Speech I/O, a subject of intensive development, is a good example; when would the benefits of this technology compensate for the substantially *lower* data transfer rate imposed on the user?

The Other Disciplines

Sociologists. This group of HCI researchers are focussed on the social and organizational aspects of human-computer interaction, such as the effects of computerization on an organization. This work is clearly very important to everyone concerned with the impact of computers. There are some unexplored aspects of the social implications of system usability. For example, computer specialists of the "wizard" variety take on a certain social role within their organizations. Perhaps such people have a vested interest in the computer systems remaining only poorly usable because it enhances their own role. Such

computer experts tend to be male, which is perhaps related to the prototypical wizard's desire to have a "macho" mastery of the system, or a member of the secret club or priesthood. Thus there are aspects of usability that relate to the social organizations associated with computing; these have not been adequately researched. It is possible that such social aspects are a major source of resistance opposing more usable, efficient software.

Framework seekers. Some groups within HCI apparently believe that the human-computer interaction situation is special enough, or unusual enough, that radically new frameworks for understanding human activity are required to adequately understand how people interact with computers. A more radical assertion is that approaches based on conventional experimental psychology, such as standard human factors, are inapplicable to HCI. For example, it is argued that there are radical effects of context which render standard methodologies inappropriate. It is very hard to characterize these approaches in any more detail; to the extent that they are radically new frameworks, they do not translate well to anyone who has not become acclimated to them. But such assertions are premature; experimental psychology approaches in HF have not really been applied widely and thoroughly enough yet to support any judgment that they are not effective. Furthermore, once one trims out the rhetoric, the arguments of the framework seekers seem to be very straightforward within a conventional human factors framework.

Approaches to User Interface Design

The content of the HCI field can be broken into three major segments: the traditional human factors approach, the engineering approach, and the technology and techniques for implementing user interfaces. This last topic is fairly well represented in a variety of sources, such as the Baecker and Buxton (1987) book of readings, and is often emphasized in HCI courses offered in computer science departments. This topic will not be dealt with here, since it is mainly a matter of technology, as opposed to the specifically human-related aspects of HCI.

Why HCI is Different from HF

HCI is different from HF primarily in the fact that the scope and nature of user interface design problems are not well handled by standard human factors techniques and knowledge (Reisner, 1987). The basic problem is that computers are more cognitive in their demands; normally the displays are clearly

visible, and the input devices are easy to operate. The difficulties in interacting with computers are in understanding *what to do,* not in actually doing it. Thus key aspects of computer system usability go well beyond traditional human factors concerns and knowledge. Some of these concerns will be described more below.

Another source of differences between HCI and HF is that the demands on the user interface design and evaluation methodologies are more strenuous than in conventional human factors. The standard human factors approach to user interface design has only one basic design methodology: First, try to get human factors specifications included in the overall system design specifications. Often this cannot be accomplished, at least not in any highly specific way. Second, the human factors specialist specifies or criticizes a design; usually he or she is required to criticize an engineer's design using guidelines or experience and intuition. If possible the design is tested and evaluated, using mock-ups if early in the design process, or using prototypes or a first version of the system, if late. An effort is made to determine if the system meets the human factors specifications, if any were included, and using informal observational methods to determine if there are any problems. The human factors specialist tries to get the design revised to solve the problems; it is normally impossible to make even worthwhile changes if it is late in the system development process.

It is difficult to use the standard approach of empirical testing of prototypes for computer interfaces. First, there is an extremely large number of different possible interface designs, even based on just a standard video display and keyboard. Thus, it is essentially impossible to carry out a systematic program of empirical studies that will identify what particular features of interfaces are good. Another problem is that the current cycle time of product development within the computer industry is far too rapid for standard evaluation methodology. Software developers usually can not wait for a prototype to be built, evaluated, and modified. Typically a product is released for sale at the same time as it becomes testable using conventional methodologies. Notice also that some forms of empirical comparison are essentially impractical, such as the assessment of transfer or consistency between two related products. It is essentially impossible to examine this empirically because construction and iteration over multiple prototypes is required along with two extensive training sessions to determine the transfer relationships.

Thus, the basic problem with the standard human factors methodology is that it is too slow for current software development life cycles. The proposed solution is the early involvement of human factors considerations in the design process, and rapid prototyping methodology for quick development. The con-

cept is thus to use the traditional approach, but to get results quickly. But current experience is that it is still hard to obtain human factors evaluations rapidly enough to properly drive the development process. Even if the rapid prototyping methods allow mock-up interfaces to be developed quickly, testing human subjects and analyzing the resulting data is still a relatively slow process.

Engineering Approach to User Interface Design

The basic concept of this approach is that a user interface should be *engineered,* that is based on analysis and calculation, rather than on empirical evaluations of an implemented system. An analogy could be made: Traditional human factors methods for developing user interfaces correspond to designing a bridge by following guidelines to construct a bridge that "looks okay" and then driving trucks over it to test the structural integrity of the bridge. If cracks appear in the structure, or structural members begin to bend, then the bridge is either patched up, or torn down and a new one constructed according to an improved design. Then the test is repeated. This is reminiscent of how large structures such as cathedrals were constructed in medieval times. Master builders worked "by the seat of the pants" and very often had correct intuitions. However, occasionally their intuitions were wrong and they often overbuilt, and sometimes under-built, resulting in cracking pillars or even structural collapse. Of course, what we think of as engineering today involves evaluating a design while it is still in the paper stage; the designer performs various calculations and looks up general information about strengths of materials. The calculation shows whether the bridge is acceptably strong for the intended loads. Only after the paper design has been completed, is the actual construction undertaken. Normally, and almost always, the constructed bridge is satisfactory. Rarely, some new phenomenon is uncovered such as the famous bridge collapse which led to the consideration of aerodynamic factors in bridge design. However, many thousands of bridges have been designed without empirical testing of prototypes, but with analysis and calculation before construction. This is what I mean by engineering.

Thus, in the engineering approach to user interface design, *analytic models* are used to predict usability from design descriptions or simulations. This is a rapid approach because working on paper or with computer software or simulations does not require any mock-ups or prototypes to be built, nor is there a need to run experiments with human subjects. However, the engineering approach is clearly not complete, so some empirical testing will be required for reliable system development. So the goal of the approach is

modest, in that the effort is to try to get the interface design mostly right beforehand, working "on paper" as much as possible. The slow and expensive user testing would be reserved for fine tuning, checking, or for protection against major conceptual errors, rather than being the workhorse for routine aspects of the design. Notice that traditional human factors has many precedents for analytic approaches, such as visual task design and work analysis methods. Needless to say, this type of approach is the mainstay of conventional engineering as well.

Card, Moran, and Newell presented the engineering approach to user interface design in their 1983 book. My long-time collaborator, Peter Polson, and I were independently educated on this concept by our sponsors and critics at IBM. That is, for the human factors specialists to hold their own in disputes with hardware or software engineers, they should be able to supply quantitative estimates at the beginning of the design stage. These quantitative usability estimates allow usability to be specified in a testable and objective way, which is a critical management need (Bennett, 1986; Whiteside, Bennett, & Holtzblatt, 1988), and also allow usability to be traded off with other aspects of the design in a reasonable fashion, on a par with these other aspects. For example, the design team could make an informed decision whether a 10% increase in the product's cost is worth a 10% decrease in the time required to perform tasks. Furthermore, if these usability estimates can be calculated or predicted from initial design drafts or specifications, then the design can be iterated without the construction of any kind of prototype, and without the collection of actual empirical data. This allows the user interface to be developed on the same time scale as modern hardware and software engineering practice requires. For example, the IBM PC was developed and brought to market in roughly one year; anyone who has participated in any kind of human subject experimentation knows that no more than a couple of formal tests could have been accomplished in that amount of time.

As described by Card, Moran, and Newell (1983), the engineering approach has three aspects: *Calculation* of quantitative estimates of human performance needs to be possible. Psychologists have underestimated the extent to which such calculations are possible; most psychological research has been concerned with testing contrasting hypotheses and not with estimating parameters of human information processing. The Model Human Processor, as described more below, contains pervasive parameter estimates that can be used as a basis for calculation of human performance. Along with calculation goes the concept of *approximation.* Most psychological research has consisted of nitpicking over very small effects that have strong theoretical implications. For practical engineering we need to know what kind of approximate calculations

can be made, and what their limits are. Finally, *task analysis* is a key part of the engineering approach. Much of human activity is determined by the person's *task,* rather than the person's internal cognitive mechanisms (Simon, 1969). Thus a critical step in designing a user interface will be to describe the user's task in great detail, at a level where the task constrains the user's activity. That is, the description includes the details of exactly what a user has to do to accomplish some goal; this is determined by the specifics of the user interface: which commands have to be entered at what time, where the mouse cursor has to be positioned, and so forth. Any attempt to define a user interface without such detailed consideration is flawed, since it is not tapping into the aspects of the task context that in fact most strongly govern the user's behavior.

Limitations of Engineering Models

There are some important limitations of the current engineering approach to user interface design. The major limitation is that these methods can deal only with situations in which the human is tightly constrained by the task; according to the rationality principle, only here is there a relatively sound basis for predicting what the user will do. Thus it is useful to distinguish between the "creative" parts of a task, such as composing the content of a document, from the routine parts of the task, such as making specified changes to a document with a word processor. Both standard human factors and the engineering approach can assist in designing the routine parts of the task, but not the more creative parts. Notice that many creative tasks, such as electronic circuit design, might be considered creative overall, but have many routine subsections. Notice also that if one is using a computerized tool, such as a CAD system, to accomplish a creative task, interacting with the tool should certainly be routine rather than creative. Hence, just because a task has substantial creative content is no excuse for implementing a poorly designed user interface. In fact, in creative situations, good design of the user interface is even more essential, because the user should be free to concentrate on the truly creative parts of the task, rather than expending effort on trying to master what is supposed to be a routinely usable tool.

A second limitation of the current engineering approach is that it does not contribute much when the required information is heavily perceptual or motor in nature, or parametric in that it depends not on the task or general principles, but strictly on the parameters of human performance. Examples are the legibility of characters on a screen and the confusability of icons. This is where traditional human factors results and methods are in fact the strongest. So on

the whole, the correct way to view the contrast between the engineering approach and the standard human factors approach is that they are *complementary*; engineering methods based on GOMS task analysis provide a strong approach to specifying the task-driven aspects of the user interface, whereas standard human factors methodology is best for choosing those parts of the interface that depend on empirically determined properties of human performance.

Survey of HCI Concepts

The following survey of the content of the HCI field is of course very superficial, and represents a particular point of view. Given the diversity of the HCI field, many of those active in HCI would disagree with the particular view presented here.

HCI Sources

Research sources. The single most important book is *The Psychology of Human-Computer Interaction,* Card, Moran, and Newell (1983), which presents an engineering-oriented approach to HCI which will be described more below. The book is dated, and there are many problems with the experimental data presented in it. However it remains a unique and indispensable source in this field because it presents the Model Human Processor, the GOMS model of HCI, the Keystroke-Level Model for analyzing user interfaces, and an exemplary piece of work on the quantitative modeling of text selection devices. These topics will be described more below.

The single book most worth having is the *Handbook of Human-Computer Interaction* edited by Helander (1988). This book has a large number of specific chapters covering most of the scope of human-computer interaction, many of them directly usable to the practitioner. Two important edited volumes are the Norman and Draper (1986) volume on *User Centered System Design,* which is highly regarded for its conceptual discussion but does not present much in the way of specific design issues or methods. The volume edited by Carroll (1987) contains many important early research papers on HCI.

A key research outlet is the *Proceedings* of the Annual Conference of the ACM Special Interest Group on Computer-Human Interaction Conference (SIGCHI). Many researchers present short papers at this meeting, and so the published proceedings have interesting and important research results. The problem is that few of these papers go on to be published in a more substantial

form, reflecting the fact that the HCI field has not settled upon a single set of primary journals closely associated with HCI.

Textbooks. Textbooks normally provide a survey of the core of a field, but the available HCI textbooks are very weak. Perhaps the earliest popular textbook is Rubenstein and Hersh (1984); however it appears to be written for a management audience rather than a student audience. It is extremely informal, and as a result, is often hard to apply and is not very deep or specific. But this book does do an excellent job of laying out some important issues and making some important distinctions that are missing in other sources. The textbook by Shneiderman (1987) has a good coverage of topics, and is much more specific and applicable than the Rubenstein and Hersh book. However the quality of discussion and interpretation of results is often very erratic, and is not clear who the intended audience is; the treatment of experimental results is appropriate neither for experimental psychologists or HF specialists, nor for computer scientists. Comprehensive and coherent integrations of empirical results are lacking.

Bailey's (1989) text is an interesting oddity. It is a mixture of traditional human factors and the basics of HCI. Standard human factors textbook fare, such as speech communication and the design of knobs and dials (which are extremely rare on today's computers) is presented, though it has little direct relevance to HCI. Finally Baecker and Buxton (1987) is a large and comprehensive collection of readings. It includes quite a bit on the design and implementation of user interfaces but some other key material is not well represented.

General Design Issues

Usability as a design goal. An important activity for HCI specialists is to document cases where poor user interfaces have essentially destroyed the functionality of a product. These cases can be used to help persuade computer scientists and product development managers that user interface quality is important. A favorite case is Frye and Soloway (1987) in which the user interface of a popular piece of educational software was so difficult that the only children who could successfully use the software were those who already understood the mathematical concepts that the software was supposed to teach. Thus a poor interface can make a piece of software pointless.

On the other hand, a paper by Göransson, Lind, Pettersson, Sandblad, and Schwalbe (1987) makes the equally valuable point that sometimes the user interface is *not* the problem. There are many system design problems, issues

of functionality, and overall usability that are not a result of a poor user interface, but rather are due to a bad match between the overall user's task and the functions offered by the computer system. For example, after rewriting a database access system used in a business organization to make it more usable, the developers discovered that in fact the business organization had no apparent need for the database at all. In another example, the extremely difficult problems of a multiple-access scheduling system for a medical clinic disappeared when it was realized that the more fundamental problem was that the medical clinic was far too large anyway. When the clinic was broken down into smaller units that were more responsive to patients, the need for an elaborate scheduling system was eliminated.

Designing for usability. The traditional design process for a user interface is similar to that in standard human factors. It consists of using guidelines in the initial stages of the design, followed by some type of user performance testing of a prototype, which can be as simple as sketches on pieces of paper. The designer should then iterate the design until a satisfactory result is achieved. Gould (1988) has an excellent presentation of this process, based on actual experience, and which presents many specific pointers and suggestions.

A fundamental issue in system design is how users should understand the system. This is a topic in what can be termed *conceptual models* or *mental models.* This is a difficult issue for theoretical psychology, and many unclear discussions and muddled terminology are present in the literature. Two good discussions of this topic are in Rubenstein and Hersh (1984), and in Kieras (1988a, 1988b). One basic issue is the familiarity of the system, or the value of the *metaphor* or overall concept of the system that the user is invited to learn. For example, in business settings, an interface that resembles traditional paper forms is often a very easy one for users to understand. In contrast, a database retrieval system using Boolean expressions does not resemble any conventional business device, and one can expect users to have more difficulty learning to use it. A second issue is the extent to which the user needs to understand the internal workings of the system, as opposed to being able to work at the "outside" level of the system. Many traditional computer systems seem to demand a fundamental understanding of the internals of the system, possibly at a superficial level of analysis, but directly in terms of the actual mechanisms and processes in the system. It seems more desirable for the user interface to hide these mechanisms, so that the user does not need to know the internal operations of the system. A good example is the Macintosh interface, which goes a long way towards concealing many traditional computer system concepts; indeed, it seems that many traditional computer experts have been temporarily confused by the invisibility of the underlying system. For

example, installing an operating system is normally a subtle process; on the Macintosh it is almost trivial.

User Interface Styles

User interfaces come in different styles, such as menus, command language, forms, and direct manipulation. Shneiderman (1987) presents a good overall survey of the different user interface styles, and lists advantages and disadvantages of each. This discussion will be elaborated by making use of more recent results.

Menus. A classic problem in menu design is the question of whether menus should be broad (many choices), or deep (many levels, few choices). The traditional advice is to limit the number of choices on a screen to about 7, but this limit was never given a substantial justification other than it being related to short-term memory (STM) capacity, but the relation of STM capacity to menu usage was never analyzed in enough detail to justify this guideline. A special case of menu interfaces has been analyzed on a quantitative basis by Landauer and Nachbar (1985). The time to arrive at a final selection of a number in a touch-screen menu interface was a combination of Fitts' Law and Hicks' Law. The specific parameters suggest that if the user can rapidly locate a menu item on the screen, broad rather than deep menus would be preferable. However, Landauer and Nachbar point out that the actual design decision should be based on the quantitative specifics of visual search time versus choice response time. Somberg (1987) showed that maintaining menu items in the same position in a mouse-based pull down menu system was a better solution for long-term use than various clever ways of rearranging the order of menu items dynamically. Shneiderman (1987) presents a good discussion of what he terms the *BLT* menu interface; an example is the menu interface used in the Lotus 1-2-3 spreadsheet program. In this type of interface, each menu choice can be selected by typing in the first letter of the menu item. The items in each menu have been selected so that they have a unique first letter that is reasonably mnemonic, but this same letter might be used in other menus. The interface is designed so that these first letter items can be typed in as a stream, and the menu system immediately moves from one menu to the other. If the user stops typing and looks up at the screen, they see the menu corresponding to the last item they typed.

The BLT interface is an especially interesting and valuable form of menu interface because the mnemonic single letter items function as commands that the user can learn *incidentally* while using the menu system. For example, in

Lotus 1-2-3, the user can type *RFC2* which corresponds to the command "Range Format Currency 2 decimal places" and can learn this command string "along the way" without a specific memorization effort, or referring to the manual, or learning arbitrary command keys. If at any point the user does not remember the next letter in the command string, the user can simply look at the screen and drop back into menu-following mode. A similar type of interface, except normally only one command at a time, appears in the Macintosh. By convention, single-keystroke shortcut symbols ("power keys" or "hot keys") are displayed next to heavily used menu items so that the user has immediate access to the definitions and can learn them as convenient, and at any time can revert to using the ordinary menu selection methods. Thus the user can make a seamless transition from beginning user to "power user" of an interface, with *no penalties* along the way.

Experts vs. new users—a false tradeoff. It has long been assumed that there is a necessary tradeoff between an interface that is suitable for new users and one that is suitable for experienced experts. The BLT menu, described above, is one way in which this apparent tradeoff can be circumvented. However, a key study by Whiteside, Jones, Levy, and Wixon (1985) shows that in general the tradeoff is not true. Whiteside *et al.* studied several different operating systems that used different interface styles. Users with different backgrounds learned how to use the systems and then carried out a set of benchmark tasks. On the whole, those systems that were easiest to learn were also those that were fastest and easiest to use. A similar conclusion was reached by Roberts and Moran (1983) in a classic study of text editors. Whiteside *et al.* conclude that the *quality* of an interface implementation, the many small details involved in producing a good interface, were more important than the overall interface style.

Command languages. Command language interfaces are the traditional form of interface largely because they are relatively easy to implement, having appeared in the very first batch systems, and then the first interactive systems. However command languages are typically difficult to learn. The studies in the field have not made this issue very clear, but a variety of studies suggest that some command language organizations are fundamentally easier to learn than others (Shneiderman, 1987). My argument is that the basic difficulty of a command language is related to the difficulty of *synthesizing* a command; that is, users must be able to create commands, not simply perform verbatim recall of the exact form of the command. Taking advantage of this concept, a new class of command language interfaces could be defined that are much easier to learn and to use than existing ones. One example is *cross-product* command languages, in which commands are composed by combining a small

set of action-designating verbs with a small set of object-designating nouns. Thus, instead of an individual special command for each combination of object or action, the user can instead learn a small set of action verbs and object verbs and synthesize commands based just on these two small sets. A similar argument applies to the difficulty of command abbreviation schemes, which is a heavily researched topic (Shneiderman, 1987, for a review). In both cases it appears that the basic governor of difficulty is the consistency and extent of a pattern in the commands or abbreviations that reduces the amount of special case memorization and verbatim retrieval that the user must perform.

Direct manipulation. Direct manipulation interfaces are those in which by using some kind of pointing device, typically a mouse, the user controls the computer by manipulating objects on the display in some form of intuitive and straightforward way, normally manipulating objects spatially with physical actions, rather than linguistically structured commands. But *direct manipulation* is hard to define. There are various discussions in the literature, but on the whole these comments are theoretically weak or incoherent. But, the basic principle seems to be that direct manipulation interfaces are organized so that perceptual and motor activities replace activities that otherwise require extensive cognition (Elkerton and Palmiter, this conference). Thus, on the Macintosh one can copy a file from one disk to the other simply by locating it visually and then physically "dragging" the file to its destination. This activity seems indistinguishable from moving a physical document from one physical folder to another. In contrast, traditional computers require the user to synthesize an exact string of letters comprising a command, following a defined syntax which on occasion can be quite convoluted. While direct manipulation interfaces clearly work very well when there is a concrete physical and spatial metaphor to be invoked, such as moving documents about a desktop, or drawing pictures, it is unclear whether they have any advantage in processes or activities that are not inherently spatial or do not have a clear spatial metaphor. For example, although there has been considerable interest in *visual programming,* there is little evidence that it has substantial advantages compared to traditional text-oriented programming.

Environments. Another set of considerations is interface *environment,* by which is meant the entire user's environment or the user interface of the system as a whole. For example, workstations often provide access to multiple windows and various facilities such as a global text editor and window manager. Card and Henderson (1987) describe the design of a very elaborate system that provides the effect of very large amounts of organized display space. Computer systems on a local area network often have other facilities and features that produce a larger scale environment for the user than the indi-

vidual machine would normally have. Likewise, command scripts, history, and command reentry functions provide a larger scale user interface, in which users can sometimes organize their activities at a much higher level than simply at levels of individual commands. An interesting paper on this subject is Greenberg and Witten (1988) who found that in UNIX systems a small number of recently entered commands accounted for the bulk of command usage. This has strong implications for useful command reentry functions. There are many different command reentry implementations, but with very few exceptions they are extremely crude, often overly complex, and often fail to provide the type of access that the Greenberg and Witten results suggest. In my opinion, an exemplary design for command reentry appears in DEC's VMS operating system, in which the cursor keys are used to scroll forward and back through a list of recently entered commands, and to perform simple insertion and deletion editing on the recalled command before entering it. This design seems to suffice for most command reentry situations, is trivial to learn, and quite simple to operate. In contrast, other command reentry facilities, such as in MS-DOS, seem clumsy and unsuited for routine use.

Input and Output Devices and Techniques

Keyboards. The standard treatment found in Human Factors sources and the above textbooks on various cursor positioning devices and keyboards are largely applicable. However, the treatment of the standard Sholes or QWERTY keyboard is usually erroneous; the textbooks often echo the complaints of uninformed users about the "illogical" arrangement of the Sholes keyboard. The exact origin of the Sholes layout is a problem for historical research, but it is very clear from the record that Sholes systematically optimized his first typewriters for speed, engaging in a testing and evaluation program comparable with modern practice. So the most common mythical slur, that Sholes deliberately attempted to slow the typist, is clearly false. Recent work (Card, Moran, and Newell, 1983, Ch. 2) points out that the Sholes keyboard is actually relatively efficient, since it has a high proportion of alternating-hand keystrokes, which are much faster than within-hand keystrokes (Ostry, 1983). The more optimal Dvorak keyboard is estimated to be somewhat faster, but not more than about 20% faster, with some comments that the actual speed improvement may only be around 5% or so. One can hope that in the near future we will see an end to the repeated complaints and calls for improved keyboards, which only serve to distract from other more pressing user interface problems.

A related issue is the alphabetic keyboard, in which the keys are arranged in alphabetical order. These are appearing on many small computer-based devices, such as "digital diaries," but are known to be fundamentally harder to learn and slower than the Sholes layout (Norman and Fisher, 1982); the problems are: (1) almost everybody knows enough of the Sholes layout to have an advantage; (2) there is no standard alphabetic layout, so users have to learn each device from scratch, and usually must find letters by slow visual search; (3) there is little in the way of alternating-hand or other physical advantages in an alphabetic layout (Card, Moran, and Newell, 1983, Ch. 2, for an example).

Pointing devices. The comparison of different cursor positioning devices such as mice, joysticks, hand cursor keys, in most sources is usually presented in a very superficial fashion. Traditional human factors coverage of different pointing devices usually presents miscellaneous experimental comparisons which do not agree on a clear winner and so do not lead to any understanding of why one device might be better than another. An exemplary piece of work in this area is Card, Moran, and Newell, (1983, Ch. 7) discussed below, who constructed a mathematical model of cursor positioning time for each of several devices; the models provide a much more informed understanding of the benefits and deficiencies of the individual pointing devices.

Displays. The HF literature has ample discussion of the basic properties and guidelines for video displays. Several more recent interesting papers can be mentioned: Burns, Warren, and Rudisill (1986) provides a good example, with a guideline and experiment-based redesign of the space shuttle displays. Tullis (1988) provides an analytic tool based on various aspects of the display density which is clearly useful and important. Gould and his co-workers have a series of papers comparing reading speed on video displays versus paper, in which they were able to document that only the most superior computer displays compete successfully with ordinary paper printing (Gould, Alfaro, Finn, Haupt, Minuto, and Salaun, 1987). Wise (1986), Eastman, Woods, and Elm (1986), and Kieras (1988c) discuss the design and properties of graphic diagram displays.

Helping Users

Errors and messages. There are two key concepts to how a system should respond to user errors and what messages the system should produce in response to an error; these principles are articulated well by Rubenstein and Hersh (1984). First, wherever possible, the user interface should be designed

to eliminate user errors, by making them impossible to produce. For example, a menu interface can simply refuse to allow the user to select an invalid option. An example is how the Macintosh interface presents invalid menu choices in gray and does not allow them to be selected. As explained by Rubenstein and Hersh, the concept is to ensure that any errors the user makes are ones that are intelligible to the user in terms of their own problem domain. For example in a graphing program, they might accidentally select the wrong type of graph. As soon as they see the display they will recognize their error and its cause immediately.

In contrast, the traditional command language interface allows any input to be supplied at any time, regardless of whether it is a meaningful or valid action. For example, one can enter a command to copy a file to a non-existent directory and is informed of the error only after going to the trouble to create and enter the command. To a great extent, the designer's ability to follow this principle is very limited in command language interfaces. Highly efficient command reentry and editing is one way to at least alleviate these problems.

The second important principle is that messages produced by the system should tell the user *what to do* to recover from an error, as opposed to supplying a description of the error itself or its effect on the internal operation of the software. Anyone who has used computers for any length of time has received unintelligible and unhelpful error messages such as "syntax error" or "segmentation fault." In some cases, the error information is extremely obscure even to highly experienced programmers. A well-designed system will include information either on the screen, or in documentation, that specifically informs the user what to do for each possible message. An example is the documentation accompanying DEC's VMS operating system. There is a separate manual of system messages, and the following is a randomly selected sample:

> NOBITMAP, no valid storage bit map found on 'device'
>
> **Facility: BACKUP,** Backup Utility
>
> **Explanation:** The Backup Utility encountered an error during an attempt to search for the storage bit map file [000000]BITMAP.SYS;1, on the specified volume. The volume cannot be used as a save set disk.
>
> **User Action:** Retry the operation using a properly initialized Files-11 Structure Level 2 volume.

The key features of this manual are that every error is explained in a reasonable amount of technical detail, and then, the user is instructed specifically what to do to correct the problem. This is the type of information that should always be supplied for system error messages.

Documentation and online help. Training and reference documentation and online help is very poorly understood in the HCI literature. As the results described in Shneiderman (1987) show, online help is a very mixed blessing; in some studies the online help was actually detrimental. The best current research is Elkerton's (1988; Elkerton and Palmiter, 1989; Gong and Elkerton, 1990) which is based on the concept that online help should be based on a clear and explicit specification of what it is that the user actually needs to know, organized in terms of what goals the user is trying to accomplish. Elkerton and his co-workers have demonstrated that online help and training documentation can be considerably improved by basing it on the organization and content of a GOMS model, which will be described more below. This work is exemplary because it is another demonstration of how theoretically based research, along the lines of the engineering approach, can help clarify a topic much more powerfully than traditional empirically-based human factors research.

Some Engineering Models

The Model Human Processor. The Model Human Processor (MHP), presented by Card, Moran, and Newell (1983, Ch. 2), is a subset of standard cognitive theory circa 1980 intended to be an engineering model for human performance. The MHP consists of a set of processors and memories, along with numerical parameter values for each one. These components are connected in the conventional fashion; the perceptual processor receives visual and auditory input and deposits the results in the visual or auditory image store which is defined as a subset of working memory. Working memory is likewise embedded in long-term memory, a somewhat idiosyncratic arrangement, but consistent with one of the theoretical analyses in the cognitive psychology literature. The cognitive processor receives input both from working memory and long-term memory and modifies the contents of working memory. The cognitive processor is assumed to have a production-system architecture, in which IF-THEN rules are triggered by the contents of working memory and long-term memory and modify information in working memory. However, Card, Moran, and Newell did not explicitly make use of the production system architecture. The motor processor is driven by the contents of working memory, and controls muscle movements. The overall operation of the MHP is governed by a set of principles. Three important principles governing human performance are Fitts' Law, Hicks' Law, and the Power Law of Practice. Card, Moran, and Newell demonstrate how Fitts' Law and

Hicks' Law can be derived at least conceptually from the structure of the MHP. One other important general principle is the Rationality Principle, which is essentially a restatement of how behavior can be governed by the task. Humans try to accomplish their goals efficiently, given the task constraints and information processing limitations. The claim is that in user interface situations, the task structure is dominant, which means the specific design of the computer system will be a primary determinant of the user's behavior.

The engineering approach to pointing devices. The Card, Moran, and Newell (1983, Ch. 7) treatment of pointing devices is a good example of the engineering approach. Most sources in human factors and human-computer interaction are stymied when it comes to attempting to describe which pointing device is better in what situation and for what reason. This is because the standard human factors approach is simply to cite the results of individual specific experiments. Quite often, the experiments do not agree with each other, producing confusing results. Card, Moran, and Newell present the results of a quantitative analysis of a set of different pointing devices in word processing tasks. The key result is that the mouse follows Fitts' Law, and the other devices investigated are slower because movement time is governed differently, and usually in an inferior way. For example, cursor keys are linear with the "city block" (sum of X and Y) distance, making them on the average much slower than the mouse. In contrast, the mouse not only follows Fitts' Law but had the same parameters as the eye-hand system, suggesting that the mouse, when properly designed, is as good a pointing device as the eye-hand system permits. This means the mouse can be beaten only in cases where the eye-hand system is weak, such as small targets (which follows from Fitts' Law), or if extra hand movement is required beforehand, such as moving from the keyboard. But the overall point is that the proper way to evaluate human-computer interaction situations is with quantitative models of performance, not gross experimental results.

The Keystroke-Level Model. As an example of a specific engineering tool, Card, Moran, and Newell (1983, Ch. 8) present the Keystroke-Level Model for estimating execution times. This method is similar to the work measurement methods used in industrial engineering. It is based on estimating the overall time for completing a task by summing individual standard values for the lower-level parts of the task, which are the individual actions. Briefly, first one determines the sequence of operators required to execute a task, and then looks up the time for each operator. For example, non-secretarial keystrokes require about .28 s, while a typical mouse move requires about 1.1 s. The move between a mouse and a keyboard requires about .4 s. At some point in the sequence, the user may have to stop and think; this action is

represented with a *mental* operator with an estimated value of 1.35 s. The predicted execution time is simply the sum of the operator times.

The Keystroke-Level Model requires a specific task instance, so that the exact sequence of operators can be tested. However notice that this specific sequence can be based on a *proposed* design; it is not necessary to have implemented anything. Thus, this is an engineering tool in the sense that it can be used very early in design, as soon as it is possible to specify the sequence of operations. The main drawback of the method is the need for guessing where the mental operators are performed. Card, Moran, and Newell provide some heuristics, but they are incomplete and not adequately general; a better set of heuristics is badly needed.

The GOMS model. A major contribution of Card, Moran, and Newell (1983) is to present a general framework for describing the users' knowledge of how to operate a system. This knowledge is described in terms of *G*oals, *O*perators, *M*ethods, and *S*election rules, from which the acronym GOMS is obtained. The *goals* are simply what goals the user can accomplish with the system, basically what tasks can be performed. The *operators* are the basic actions that can be performed on the computer, such as keystrokes or mouse moves, but also actions on other parts of the task environment, such as turning the pages of a manuscript. The *methods* are sequences of operators that are used to accomplish a goal. Thus they are essentially procedures, but each goal has at least one method that will accomplish the goal. *Selection rules* specify which method should be applied in case there is more than one method to accomplish a goal. The selection rules contain task- or context-specific information to "steer" the user to using the most efficient method. Finally methods and goals have a hierarchical structure; methods can include operators that establish sub-goals, which in turn get accomplished by sub-methods. In the typical computer software task environment, methods and goals have a rich hierarchical structure. For example, the methods used to move the cursor are invoked by many different methods for accomplishing different tasks.

Card, Moran, and Newell collected data that supported the psychological reality of the GOMS categories. However, their mechanisms coupling the GOMS model to performance were very weak, and the evidence presented for the validity of the GOMS model as predictor of performance is not impressive. There is also no approach to how humans learn the GOMS knowledge. It seems intuitively reasonable that the more difficult or complex a system is to learn, the more elaborate and voluminous would be the GOMS model needed to represent the user's knowledge. Thus there should be some way of making use of the size or complexity of the GOMS model to predict learning. Finally Card, Moran, and Newell did not include any methodology for constructing

a GOMS model, meaning that it is unclear how and whether it can be used routinely.

The cognitive complexity model. Kieras, Polson, and Bovair, in a series of papers (Bovair, Kieras, and Polson, 1990; Kieras and Polson, 1985; Polson, 1987) presented a *cognitive complexity* approach that is based on using a production system cognitive architecture to represent GOMS models. This approach, which was implicit in the Card, Moran, and Newell analysis, but was developed independently by Kieras and Polson, makes use of the production system cognitive architecture to quantify the amount of knowledge that the user must have. Kieras and Polson saw that production rule representations of procedures had essentially the same categories of content as a GOMS model, and therefore adopted the perspective of representing GOMS models in terms of production systems. In this approach, a production system computer simulation model is constructed that can execute the same tasks as users, interacting with a simulated mock-up of the computer system, and executing a series of described tasks. The complexity of the production-rule simulation indicates the complexity of the interface to the user. Bovair, Kieras, and Polson (1990) provide the specific rules for constructing production system models that have the desired properties to enable prediction.

There are two main advantages of the cognitive complexity approach: First, it connects the GOMS model directly into mainstream cognitive theory, specifically the theoretical work on cognitive skill and learning represented by the production system cognitive architecture (Anderson, 1983, 1987). Second, the production system representation provides quantitative metrics for predicting certain aspects of usability. Basically, the number of production rules required in the representation predicts the overall learning time, while the number of shared rules between two systems or procedures predicts the amount of transfer of training. The time to execute the production rules, in terms of the number of production system cycles and the operators involved, predicts execution time. The amount of information maintained in working memory predicts the memory load imposed by a task. The current status of the cognitive complexity work is that the execution time, learning, and transfer predictions are very well supported across a set of different tasks, different experiments, and different laboratories (Ziegler, Hoppe, and Fähnrich, 1986). At this time there has been no work on the memory load predictions (but see Bovair, Kieras and Polson, 1990).

The applicability of the approach to practical design is more problematic (Kieras, 1988d, 1988e). Constructing production rule models is a difficult task that requires substantial expertise in artificial intelligence or cognitive simulation, and is obviously too technically demanding for routine use in practical

interface design. But the real problem is not the production rule programming, but carrying out the detailed task analysis from which the GOMS model is constructed. While considerable work has been done on task analysis in the context of human factors, a GOMS-based task analysis is a specific form in which the analyst expresses all of the methods that the user requires to actually carry out the overall task goals. When properly conducted, a GOMS analysis starts from overall user goals, and goes down the full goal hierarchy until at the bottom it describes the methods that consist of actual sequences of motor actions. Most traditional human factors methods of task analysis stop far short of this level of detail, often being little more than a listing of action-object pairs, which in a GOMS model framework, is usually only the middle-level task goals.

Kieras proposed a methodology for constructing and using a GOMS model (Kieras, 1988d). He provides a set of guidelines for decomposing a task, a simple notation for expressing GOMS models, and a recipe for constructing a model in this notation. Calculational procedures are presented for estimating learning and execution time, based on the relationship of the GOMS model notation to the production system models. Finally, both in Kieras (1988d) and in Card, Moran, and Newell (1983, Ch. 12), are suggestions for how a design can be refined based on properties of the GOMS model representation. These and some other design principles will be described in the next section.

Some GOMS-Based Design Guidelines

These guidelines are based on implications of the GOMS model and the concepts of cognitive skill used in the cognitive complexity approach. The overall concept is that the user acquires and uses procedural knowledge in HCI situations. The procedural knowledge is organized in terms of a GOMS model, and is acquired either from explicit descriptions (e.g., instructions, see Bovair and Kieras, in press) or from problem solving activities based on various kinds of knowledge, including trial and error (Card, Moran, and Newell, 1983, Ch. 11). With practice, the procedural knowledge becomes refined and routinely invoked, as is described in the analyses of the development of cognitive skill (Anderson 1983, 1987; Card, Moran, and Newell, 1983, Ch. 11). With extreme amounts of practice, the procedures should become automated and require very little cognitive processing capacity; however the actual boundaries of automation in computer usage have not been explored. It is possible that only the most heavily used activities, such as cursor movement or a few stereotypical command sequences, achieve an automated state for most users.

Interface organization should be in terms of the users' goals and methods. The interface should be organized and presented in terms of the user's perception of the task, not the programmer's. This is a standard guideline within human factors, but if the designer has explicitly developed a GOMS model that describes how the user is supposed to accomplish goals given a particular system design, then the designer is in a position to compare the explicitly developed goals with the structure and specific content of the interface. For example, the designer can compare the menu hierarchy to the goal hierarchy in the GOMS model, and consider whether the individual words used in the menus are recognizable as user's goals. Because the task structure has been made explicit in the GOMS model, the designer now has a specification for how the user interface should be organized.

The documentation should present all of the components of a GOMS model for the task, and provide for access in terms of the user's goals. This point is discussed more extensively in Elkerton (1988; Elkerton and Palmiter, 1989; Gong and Elkerton, 1990). As Elkerton's work shows very elegantly, explicitly providing methods in the context of a goal-hierarchical organization radically improves people's ability to learn how to perform tasks using documentation or online help. The major problems with conventional user documentation become clear from the perspective of the GOMS framework. Users typically know at least the high level goals that they want to accomplish. If they do not know how to use the computer system, it is because they do not know the *methods* required to accomplish those goals. Thus a user will be entering documentation or online help with a set of *goals* in mind, and will be in search of *methods*. However, the content of most documentation and online help is radically unsuited for users in this state of mind. Most documentation in fact consists essentially of *operator* documentation. The individual commands are presented, along with their specific syntax and so forth, but without any description of what sequences of commands should be used to accomplish something (methods), or why a particular command would be used (goals), or in what particular situation (selection rules). Even in the context of Macintosh software, the documentation often consists of a detailed description of the effect of each individual menu choice. Thus the documentation rarely presents methods, and rarely presents the document organized in terms of the higher level goals a user might want to accomplish. Typically the user is reduced to scanning the documentation, perhaps aided by clever guesses, in an attempt to find information that can be used to deduce or infer a method. Finally, documentation rarely includes selection rules. Thus there are often multiple methods to accomplish a particular goal but the user is in the position of having to infer or deduce their own selection rules for making use of the

different methods. A common result is that the user will be stuck to using a method which is extremely inefficient, because they have received no guidance to the existence of more efficient methods.

Every high-frequency critical task goal should have a simple method. This is the basic rule for user interface design, but it is often ignored in practice. The designer can identify the goals which are important and frequently accomplished in a task situation and then ensure that the corresponding method is simple and efficient.

Every goal should have only one method, unless there are specific reasons for multiple methods. Unnecessary methods just add opportunities for the user being confused and making errors, as well as increasing the total time required to learn how to use the system. If there are multiple methods for a goal, it should be possible to state a simple and clear selection rule for using each method; if this is not possible, it is a strong clue that the method should be eliminated—it is either too specialized, or has no clear function.

Similar goals should have similar methods. A key result from the work of Kieras, Polson, and Bovair, (Bovair, Kieras, and Polson, 1990; Kieras and Bovair, 1986; Polson, Bovair, and Kieras, 1987) and related work by Singley and Anderson (1987–1988), is that the effects of positive transfer in computer interfaces are extremely large. In fact, a common result found by Kieras, Polson, and Bovair in various studies was that the extent of transfer, as measured by the number of shared production rules, was a more powerful predictor of training time than the individual subject's own mean training time! This suggests that developing "consistent" methods that maximize the amount of positive transfer is a prime way to reduce the time required to learn a system. This form of "consistency," which can be termed *method consistency,* is basically that similar goals should have similar methods, where the methods have been articulated at the detailed keystroke level. Rough similarity at a high level, or visual similarity in the interface, will not ensure transfer.

Two approaches to ensuring transfer can be listed: first, high-level methods should share lower-level methods as much as possible. For example, all selection of text should be done in the same way, regardless of what higher-level operations or mode is involved. This form of consistency reduces the total number of methods to be learned and prevents mode errors. Second, conceptually similar goals should have a generalizable method that covers them all. For example, in many word processors, the *move-text* goal and the *copy-text* goal are accomplished by almost identical methods. A heuristic for identifying similar methods at this level is whether one can substitute one name or concept throughout the complete first method to obtain the second. If the entire method could not be obtained, being able to obtain a sizeable

contiguous subset of the second method should be adequate. Based on the available data, one would have to say if method consistency is not present, the interface is seriously flawed. However, there are many opportunities for method consistency in interfaces that often go unexploited.

Error recovery should be possible with routine methods and a minimum of problem solving. The criteria for good error recovery described above can be stated somewhat more precisely in the context of the GOMS model and cognitive skill concepts. If the user can simply learn one method for backing out or canceling an error, this allows users to recover routinely instead of having to engage in problem solving. If the error messages supply or identify a method for recovery, the user can simply read and execute this method instead of engaging in problem solving to discover a method. Finally, permitting the user to simply retry or reenter a command takes into account the routine and sometimes automated nature of many methods. If a trivial error has occurred, it may often be easiest to simply rerun the method. Such schemes as negotiated error recovery can require the user to learn an unnecessarily complex set of methods or to engage in problem solving to try to figure out what the system wants.

What the HCI Field Needs

Traditionally, human factors specialists have always been concerned about the credibility of human factors within the engineering community, voicing a standard complaint that designers do not give adequate recognition to human factors concerns until it is too late. Likewise, user interface design and other aspects of HCI also have a credibility problem within the computer industry and academic computer science. What is needed to bolster this credibility is multiple and highly visible demonstrations of the value of HCI effort in developing successful systems. In addition, it is critical for practitioners and researchers in the HCI field to have obvious computer expertise, and more computer science students should be taught HCI concepts and techniques in the universities.

My perspective is that there should be more research on the engineering approach, because this is the approach that will make the most sense to the technologists, the computer scientists and engineers who normally control the product development process. The research should emphasize approaches that are rigorous and simple enough to be taught to computer science practitioners and to be applied in actual design situations.

Finally, HCI needs more opportunities to validate its proposed methodologies and concepts in the context of actual product design. Even approaches

as well developed as the cognitive complexity model remain laboratory methods, and at present we have very little information on whether they have practical significance in the design of actual systems. The HCI field needs to gain experience in actual design problems, and take this experience back to the development of the theory and practice of user interface design.

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The Effects of Rapid Prototyping on User Behavior in System Design

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ABSTRACT

Rapid prototyping is a design, development, and evaluation process that creates successively refined hardware or software models representing the current conceptualization of a product in design. Aeronautical and marine engineeers, for example, use engineering prototypes of operator displays in simulators for aircraft or ship cockpit/control room design. Architects use hardware models as partial prototypes of their designs. Today's software environments provide system designers with the ability to build system prototypes with relative ease. This method allows system designers to build demonstrations that are very effective for users' formative evaluation. Rapid prototyping research and development tools have a significant effect on how system designs are perceived by potential users of the designs and the systems. Prototyping and its goals are defined and descriptions are provided of user participation in system design, the impact of rapid prototyping on user behavior, and examples of how rapid prototyping has been used to impact user expectations. The examples focus on intelligent tutoring systems, a pilot-vehicle interface, and graphical displays for maintenance problem solving.

Introduction

Prototyping is a design, development, and evaluation process used to create hardware and/or software models that represent the current conceptualization of a system or object design. Rapid prototyping refers to the development process whereby several iterations of prototypes are generated, evaluated, and revised before the final system is implemented. The terms prototyping and rapid prototyping will be used interchangeably throughout the paper. This paper will focus on prototyping as it relates to complex human-machine system

design. In particular it examines the effects rapid prototyping may have on the behaviors of individuals involved in the design, development, and operation of a system. Such systems carry out functions and have an interface through which a human may interact. These systems span a range of possibilities including information systems, training systems, vehicle systems, processing plant systems, and manufacturing systems.

For example, in vehicle systems, the U.S. Navy uses a full-scale mockup of submarine command and control centers for the design and layout of the complete physical environment. This includes everything from console and other equipment placement to new user interfaces on the console screens (Wallin, 1988). Similarly, the U.S. Air Force relies on rapid prototyping for research related to advanced avionics systems (Duke, *et al.*, 1989). In advanced avionics systems environments, control law concepts, alternate vehicle control algorithms, pilot controls, and cockpit displays are implemented and tested in a series of advanced-systems prototypes. In these and other such prototyping environments, it is possible to iterate through many different configurations for evaluation and subsequent design (for other examples see Cieslak, *et al.*, 1989; Hays, 1989; Lewis, et al., 1989; Saxena & Kaul, 1986).

These and other current development environments provide system designers the ability to construct system prototypes with relative ease. These prototypes may contain as much or as little of the purpose, function, and form of the system as is desired for evaluation. The latest development methods promote incremental design and development in an iterative process. These methods allow today's designers to build demonstrations that are very effective for evaluation. Such rapid prototyping research and development tools have a significant effect on how designs are perceived by everyone in the design process, from on-line users through system maintainers and managers.

Rapid prototyping presents several prospects for the design and development of complex systems. Designers are now able to provide concrete examples of their designs to users for feedback, to try out new design ideas with minimal investment, to clarify their own ideas through successive prototype iterations, and to involve end-users and managers in design; to name but a few of the prospects (cf. Belardo & Karwan, 1986; Floyd, 1984; Stevens, 1983). Designers also are able to obtain, from themselves and others, evaluations of efficacy, efficiency, utility, and overall acceptability of their design concepts before the designs or implementations become too expensive to change (Cerveny, Garrity, & Sanders, 1986). In effect, prototyping provides a fertile ground for shaping both the system under development and the behaviors of all people involved in the design, development, and use of the system. However, to make the most of this potential, it is necessary to develop

a clear understanding of prototyping and its behavioral implications. The rest of this paper examines prototyping as a methodology, discusses the users and behaviors affected by prototyping, and provides examples of rapid prototyping as it impacts user behaviors. The paper closes with a discussion of directions for rapid prototyping and resulting behavioral change in the system development process.

General View of Prototyping

The following discussion examines literature on prototyping and integrates this literature into a general framework defining goals of prototyping, kinds of prototyping, individuals affected by prototyping, and the behaviors of these individuals as they are affected by prototyping. Since the complex systems under consideration are primarily software-driven, much of the literature examined is software-based work.

Goals of Prototyping

Each particular definition of prototyping and prototypes contains the theme that a prototype is a model of the operational system. However, these and other characterizations of prototyping (Carey & Mason, 1983; Harker, 1988; and Jordan, *et al.*, 1989) all modify the definition to align with the goal of the prototype. For example, if an automobile manufacturer's goal is to test consumer appeal then the prototype of a new automobile must be a fully operational vehicle that can be tested for qualities such as handling, aesthetics, comfort, and power. Other automotive prototypes may place emphasis on other factors such as manufacturability. From another perspective, if the goal is to evaluate display utility then a prototype for evaluating a computerized display for a nuclear power plant operator's panel need only have the display concept depicted. Such a prototype would attend less to interface software or to simulations of the plant instrumentation systems. Consequently, we must specify the goals of prototyping before we can define the different kinds of prototyping and their effects on individuals.

There are three distinct views of rapid prototyping. These are discussed in turn and then integrated. Bally, Brittain, & Wagner (1977) provide the earliest and simplest view in their discussion of three goals for prototyping. One is to increase user confidence in the system. Another is to increase the learnability of the system. The third is to provide the user early experience with the system.

Developing a more comprehensive view, Floyd (1984) discusses several goals which may be clustered into three primary goals that she also classifies

as kinds of prototyping. One goal is to *explore ideas,* examples of which are clarifying requirements, developing new features, and structuring implementation. Another goal is *experimentation,* examples of which are determining efficiency of the system or demonstrating technical feasibility. The third goal is *evolutionary adaptation* which consists of a system adapting gradually to a changing environment. This view incorporates that of Carey & Mason (1983) who said the goals of prototyping are to improve the development of and definitions of requirements.

Mosty recently, Verrjin-Stuart & Anzenhofer (1988) suggested the goals of prototyping are:

1. evaluate organizational impact
2. establish requirements and data structures
3. develop human-machine interface
4. establish data definitions
5. anticipate possible system changes
6. determine operational efficiency

Their ideas are a general integration of several views. One view is Alavi's (1984) five goals which are to obtain user input and feedback, to increase user commitment to the system, to promote relations among developers, operators, and supporters, to increase likelihood of a "right" system, and to clarify requirements and functions. Another is Belardo & Karwan's (1986) goals which are to pique the user's interest, to increase user satisfaction, and to increase managerial dedication. The final view is Cerveny, Garrity, & Sanders' (1986) which includes increased system quality, decreased resistance to change, increased user commitment, increased sense of ownership, increased effective system use, and increased user attitude toward the system.

Examination of these three views shows that there are two distinct and possibly equally important goals: 1) Affect system design, or 2) Affect system design users. Each of these has several subgoals. The goals and subgoals may be active alone or in combination with one another. This combined view yields six potential goals of rapid prototyping. The goals and subgoals are named and characterized as follows:

1. Affect system design.
   a. explore system design ideas—this includes establishing requirements, defining data structures, identifying system functions, developing interface concepts, etc.
   b. evaluate system design ideas—this incorporates experimentation and includes determining functional utility, operational efficiency, technical feasibility, etc.
   c. adapt system design ideas—this incorporates evolutionary adaptation and includes anticipating possible system changes, requirements changes, environmental changes, etc.

2. Affect system design users.
   a. impact organization—this includes improved team participation during development, increased user input and feedback, etc.
   b. educate users to the design concept—includes increased user learnability, increased experience with system, increased user interest, etc.
   c. proselytize system users (and development participants)—this includes increased user commitment, increased management commitment, increased sense of joint ownership, increased likelihood of system being considered right, etc.

These goals account for all the activities described above and may be used as the starting point for developing characterizations of prototyping, and the behaviors affected.

Definition of Prototyping

The orientation of definitions of prototyping is guided explicitly by the goal of affecting the system design. The definitions ignore the goal of affecting the system design participants. Consequently, that goal will not be addressed until the next section of the paper.

Floyd (1984) defines prototyping as a "well defined phase in the production process, where a model is produced in advance, exhibiting all the essential features of the final product, for use as test specimen and guide for further production". Morrison (1988) borrows from Boar's (1984) definition calling prototyping a "method for extracting, presenting, and refining a user's needs by building a working system. By increasingly refining (the prototype), as problems are uncovered and solutions emerge, prototyping can efficiently solve the definition problem". Tozer (1987) uses examples, saying that prototypes can be screen or report mockups, simulations, or a complete model of the final software system. Finally, Tanik and Yeh (1989) call prototyping a "process of developing a scaled-down version of a system to use in building a full-scale system. . . . The final product of the prototyping activity is a working model that can be used for many purposes, such as requirement validation, feasibility study of a complex system, behavioral specification of a system, and functional specification of a system design".

Extending and integrating this earlier work, Luqi (1989) defines prototyping as the process of creating one, or a series, of concrete executable models of selected aspects of a proposed system. The model is created as part of a larger design process which includes requirements specification followed by design, then prototype development followed by user validation. This is an interleaved process in which traditional activities such as requirements definition and functional decomposition lead to the development of an initial version of the system which will be evaluated and refined. The versions or kinds of prototypes may take on a number of forms including mockups, simulation, or complete models of the final system.

Kinds of Prototypes

There appears to be a common theme among the different kinds of prototypes available to developers. The theme, in general, is that kinds of prototypes are differentiated by the extent to which they embody or clarify the purpose, function, and/or form of a system under development. In a widely used scheme, Carey and Mason (1983) suggest three categories of prototypes:

1. scenario or simulation prototypes
2. demonstration system prototypes
3. Version 0 or working version prototypes

The first kind produces a scenario or simulation. The prototype only simulates the software system without the application logic. This embodies the purpose and some function of the system. The second kind produces a demonstration system. The prototype includes the user interface with enough background application logic to make the system work. This embodies the purpose, function, and some form of the system. The final kind of prototype is producing a Version 0 prototype, which is the first working release of the software. This embodies the complete purpose, function, and form of the system. Therefore, alternative descriptions of prototypes can be organized according to what is embodied in the prototype and then described in finer detail.

1. purpose only prototype—requirements list, statement of need, etc.
2. function only prototype—conceptual design
3. form only prototype—static mockup
4. function and purpose prototype—scenario, storyboard characterization
5. form and purpose prototype—models, simulations
6. form and function prototype—models, simulation
7. form, function, and purpose prototype—working version, Version 0

If the prototype embodies system purpose only, then a requirements document or a statement of need serves as the prototype. If the prototype embodies system function (and may include purpose) then a scenario or storyboard serves as the prototype. If the prototype embodies system form (and may include purpose and/or function) then a model, working prototype, or operational system serves as the prototype. Each of these is a candidate for early iteration and refinement with users and other design participants. Consequently, each can be affected by the participant; and, each can affect the participant.

Summary

Based on existing work, we have defined prototyping, its goals, and its kinds. In short there are goals related specifically to affecting system design and to affecting system design users. These goals may be pursued by the

development and iteration through several kinds of prototypes which vary in the degree to which they demonstrate some combination of purpose, function, and form. Each kind of prototype can be expected to have different effects on the system design and the behavior of system design users depending on who is being affected and what goals are being sought. The focus of the rest of the paper is on those effects—what they are, who they occur to, and what behaviors they impact.

Effects of Prototyping

Positive & Negative Effects of Prototyping

Prototyping has both positive and negative effects. There has been some work delineating these effects. Morrison (1988) has focused on the effects of prototyping on an artifact under development. He concludes good effects are: 1) prototypes provide immediate impact on design due to tight feedback loop, 2) dynamic interactions and development are gained, and 3) development of a working deliverable. Bad effects fall into a general category of seducing the developer into thinking a design is good when there are still problems. Some bad effects of prototyping that produce this result are that prototypes conceal system structure, tend to maintain the status quo, defer full implementation, hide exception handling, and hide complex manipulations.

Alavi (1984) has focused on the effects of prototypes on users during the development process. He concludes that good effects are increased commitment among users, better relations among users, and increased likelihood of the produced system being accepted. At the same time bad effects are possibly overselling to yield unrealistic expectations, losing management control and losing user enthusiasm (as prototypes fail or disappoint).

Bally, Brittain, & Wagner (1977) focused on the users and the overall process. They found good effects are increased user confidence in the resulting system and early learning about the system. The negative effect is that the method can be very expensive as clear development goals can get lost. Along these lines, the system may never be completed and the "best" possible design may never be reached.

Combining across these and other studies shows prototyping, as a system design method, produces three general, positive effects. One is to *increase communication* between the system user and the designer. The increased communication will result in clearer definitions of requirements and specifications. The ultimate benefit is lower development and modification costs because extensive rework is avoided. Increased communication also promotes

closer working relationships and enhanced commitment among the users in the development process. The relationships and commitment can result in a greater sense of ownership in the system developed.

A second general, positive effect is to *compel a tighter feedback loop* during the development process. This feedback may be among some or all participants in the development process and results in immediate design impact both from and on the participant. Such an impact may yield improved design characteristics and, consequently, an increased likelihood of producing a good system. The increased feedback may also produce a sense of ownership from the participants thereby resulting in greater commitment.

Finally, prototyping has the promise of *providing a working example* of the system during development. Providing this example for various users will result in a working deliverable that may be studied, evaluated, demonstrated, and possibly carried over to production. Study and evaluation provides users opportunity to learn. Demonstration helps to keep management committed to the development and may provide completion of contractual requirements. Any carryover from prototypes may reduce time and cost for final production.

Prototyping has three general, potentially negative effects. One is the potential for *failing to meet expectations.* When a prototype system is applied with a naive user population there is often the perception that the prototype is the final product. Sometimes such users cannot understand why there is such a long delay between the prototype, which seems to work, and the completed system, that looks just like the prototype. This problem is exacerbated when the user perceives that the prototype, which appears real, was completed for a very small portion of the available funding resources. It begs such questions as "you appear to be quite far along, are you sure that you need all that remaining time to complete the system"?

Related is the problem of using prototypes with naive users and the resultant feedback. Users in the earliest stage of formative evaluation may feel that the prototype system is completed. Therefore, they feel that it is not subject to modification and may develop a negative attitude toward the final system based on the prototype. The other danger is that such users cannot differentiate between the prototype and the finished product. Consequently, they may not recognize or believe that a finished product is no longer a prototype which may be changed. The result would be that users may try to suggest major changes to the finished product and be disappointed when such changes are not forthcoming.

Another negative aspect of prototyping is that it has the potential to *lead to incomplete development.* Incomplete development may be exhibited as de-

ferring full implementation in favor of prototypes or never being able to complete the implementation. During this process development goals may be lost and the management of the development process may go out of control. Consequently, there can be numerous add-on effects related to, or resulting from, incomplete development thereby making recovery exceptionally difficult.

The final negative aspect of prototyping is its potential for *producing unsatisfactory designs*. There may be tame designs which maintain the status quo. These may be ad hoc designs which oversimplify problems and/or ignore problems thereby preventing reaching the "best" design. These may be unclear designs which conceal system structure, hide exception handling, and hide complex manipulations from the developer thereby preventing adequate evaluation before final development and delivery.

The effects discussed above focus on the positive and negative effects of prototyping on the product or artifact being created. This means that the work from which these were drawn was aimed at the goal of affecting the design instead of the goal of affecting users. We now turn to the problem of examining users and their behaviors as affected by prototyping.

Users Affected by Prototyping

Users consist of all people who impact or are impacted by the system under development. The following classes of users and general activities of users are an extension of Morrison (1988) and Rockart & Flannery (1983) and are further described below.

1. sponsor—decisions about initiating and continuing system development.
2. manager—requires system outputs and controls operator activities.
3. operator—carries out all system functions.
4. supporter—provides all training and maintenance for system.
5. developer—designs and implements complete system.

The following descriptions characterize the level at which each of these users might respond to system development.

Sponsors have the power to authorize expenditures for and require specifications of a system to be developed. According to Rockart & Flannery (1983) these are indirect users who understand the purpose of the system and may only need peripheral outputs that serve those ends. This means they are possibly affected by, most interested in, or think about the system in terms of its *purpose*. Consequently, they may respond well to prototypes embodying system purpose.

Managers have the power to require outputs from a system to be developed

and need to understand the limits, capabilities, and interface to that system when developed. According to Rockart & Flannery (1983) these are intermediate users who understand the system function well enough to specify direct outputs that others will have to produce. This means they are possibly affected by, most interested in, or think about the system in terms of its *function.* Consequently, they may respond well to prototypes embodying system function.

Operators have to handle all input and output for the system to be developed and require training and understanding of the interface and all its relationships. According to Rockart & Flannery (1983) these are direct users who understand the form of the system (i.e., the look and feel of the interface) but may or may not understand the function and purpose. This means they are possibly affected by, most interested, or think about the system in terms of its *form.* It also means they may not respond well to prototypes based purely on purpose or function.

Supporters have to provide all training for and/or maintenance of the system to be developed. According to the Rockart & Flannery (1983) scheme these individuals must be both direct and intermediate users who understand the system form and function well enough to specify direct outputs that others will have to produce; and, to teach others how to produce it. This means they are possibly affected by, most interested in, or think about the system in terms of both its *form* and its *function.* Consequently, they may respond well to prototypes embodying system form and/or function. This reasoning leads to the conclusion that individuals who must support systems might be strong candidates to use during the design process since they may have a broader range of understanding of the system than anyone else.

Developers have to design and produce the system to be developed. They are required to understand the support, operation, and management of the system. Ideally, these individuals should think about the system in terms of its *purpose, function,* and *form.* In addition, it is desirable that their thinking be along the same lines as the other four classes of users in order to ensure a match between the developer's efforts and other users' needs.

Behaviors Affected by Prototyping

A review of the goals sought through prototyping, the effects of prototyping, and previous explorations of prototyping yields 14 specific user behaviors which appear to be affected by prototyping. There is not much difference among these behaviors so they will organize into more general behavioral

classes for further discussion. Twelve behaviors are those carried out by users with respect to the system and two are those carried out with respect to other users. The behaviors are listed below:

1. With respect to the system:
   a. learning about (Bally, Brittain, & Wagner, 1977; Stevens, 1983)
   b. operation of (Harker, 1988)
   c. understanding of (Stevens, 1983)
   d. commitment to (Alavi, 1984; Belardo & Karwan, 1986; Cerveny, Gerrity, & Sanders, 1986)
   e. confidence about (Bally, Brittain, & Wagner, 1977)
   f. interest in (Belardo & Karwan, 1986)
   g. involvement in (Belardo & Karwan, 1986)
   h. satisfaction with (Belardo & Karwan, 1986; Iivari & Kayalainer, 1989)
   i. acceptance of (Cerveny, Garrity, & Sanders, 1986)
   j. ownership of (Cerveny, Garrity, & Sanders, 1986)
   k. expectations of (Harker, 1988)
   l. attitude about (Cerveny, Garrity, & Sanders, 1986)
2. With respect to other individuals:
   a. communication among (Alavi, 1984; Floyd, 1984)
   b. relationships among (Alavi, 1984)

It appears that communication and relationships among individuals are more general classes of behavior comprised of many specific behaviors. In a similar way, the 12 behaviors engaged in with respect to the system can be organized into three general sets of behaviors for further discussion. These are *understanding of system, commitment to system,* and *attitude toward system.*

Understanding of the system is comprised of the behaviors indicating how well users can learn about the system, explain the system, teach about the system, and/or operate the system. Commitment to the system consists of dedication to system development, interest in system development, and involvement in system development. Attitude toward the system is comprised of the users' acceptance of the system, confidence in the system, satisfaction with the system, ownership feeling toward the system, and expectations of the system.

The behaviors just described may also be characterized as psychological states. If viewed as such, then one job of the rapid prototype is to try to affect the psychological states such that they are positively oriented toward the system under development. Even if the prototype developer does not attempt to actively change these states, he or she must be aware that the behavior or state of the users ultimately determines when system development is completed. Consequently, the prototype developer should at least be aware of the states and try to minimize any potentially negative impacts of their work.

Summary

Based on existing work, we have defined the effects of prototyping, the users who are most concerned, and what behaviors they impact. In short there are three general positive and three general negative effects that may be achieved with prototyping. These effects may be achieved with sponsors, managers, operators, supporters, and/or developers of systems. The effects impact their understanding of, commitment to, and/or attitude toward the system. To understand and/or evaluate a prototyping effort from a behavioral perspective (as opposed to a system design perspective) one must examine each of these factors explicitly. Furthermore, to plan for a prototyping effort that will be integrated with a system design effort one should also examine the goals and kinds of prototyping available to the developer. This would allow the developer to determine what kinds of prototyping would achieve particular effects therefore allowing the developer to better plan his or her efforts.

Examples of Behavioral Effects in Prototyping Applications

The remainder of this paper describes a variety of research and development applications in which rapid prototyping was used to design and develop a software application. Three distinctly different applications are used. Each application was worked on by either one or both authors. The first set of examples is based on experience in the design and development of intelligent tutoring systems for technical training. The second example is related to the design of a pilot vehicle interface for tactical aircraft. The third is related to the development of concepts and principles for electronic presentation of graphical information to maintenance technicians.

Prototyping for Intelligent Tutoring Systems

The primary purpose of the prototypes described here is to increase the communication between the ultimate system user and the designer of the software system. The prototype has the primary goal of insuring that system design is matched to user expectations. The prototypes described here prevent the unpleasant "surprises" that can be associated with system design.

Intelligent tutoring systems (ITSs) are computer-based instructional systems that capitalize on artificial intelligence technology to deliver training in a variety of applications. ITSs are characterized by having independent models of a system expert and pedagogical expert along with a dynamic model of the student. Descriptions of ITSs are treated elsewhere (Polson & Richardson, 1988; Psotka, et al., 1988; Wegner, 1987). Johnson (1988a,b,c) has argued

that the multi-disciplinary team that must work together to design and build ITSs must work very closely with the end users. Such personnel are technical instructors, instructional developers, job incumbents, students, and managers of technical training. Prototyping is the ideal method to ensure clear communication among the parties that must be involved in design and development of an ITS. This section will describe how prototyping has been used to insure that the finished ITS is an efficient and effective addition to an operational training program.

The examples used here draw from two experiences. The first is a project entitled, *Microcomputer Intelligence for Technical Training* (*MITT*). The second project is entitled, *Advanced Learning for Mobile Subscriber Equipment* (*ALM*).

Microcomputer Intelligence for Technical Training

MITT is a project that was completed in cooperation with the Air Force Human Resources Laboratory and NASA Johnson Space Center. The project was scheduled to build a prototype training system in a relatively short time. The short development cycle dictated that all parties must have a very clear understanding of the development goal at the start of the project. MITT was envisioned to be a new generation of an evolved approach to computer-based diagnostic training (Johnson, 1987). Therefore, one of the older systems called DGSIM (Johnson, *et al.*, 1986) was used as a vehicle to help the subject matter experts to understand what could be done. DGSIM was not a prototype, as defined earlier in this paper. However, it did serve to show the NASA instructors and subject matter experts ways that the new MITT ITS could be structured. The behavior of the instructors changed as they became active designers of the new system rather than passive subject matter experts that merely provided technical information as requested by the ITS scientific staff.

The first MITT prototype was completed approximately four months after the technical domain was identified. This prototype was complete, fitting the definition of Tanik and Yeh (1989) and the more sophisticated level of prototype offered by Tozer (1987). MITT was complete in program logic and in terms of user interface. The first MITT prototype was an example of what Carey and Mason (1983) called "Version 0".

The prototype of MITT was evaluated for acceptance by astronauts, flight controllers, and instructors at Johnson Space Center. Due to the sophistication of the users, it was appropriate that the prototype system be as complete as possible. Because the prototype was complete, it was very useful in obtaining a substantive list of specifications for subsequent versions of MITT.

Prototype for MITT Writer

MITT Writer is an authoring system that will permit technical training personnel to build MITT intelligent tutoring systems without using programming languages. As with the MITT system, a prototype was used to demonstrate the capabilities of the envisioned system. Since this prototype was used only to demonstrate and clarify the requirements of a complete system, it was only a scenario or simulation of the planned system. The simulation demonstrated the interface and functionality of the system in design. Such a prototype can also be called a user interface prototype.

Advanced Learning for Mobile Subscriber Equipment

ALM is the ITS for the Mobile Subscriber Equipment (MSE). MSE is the largest electronic equipment acquisition in the history of the U.S. Army. When fully fielded in 1993, it will replace nearly all the tactical (i.e., front-line) communications radios and telephones in the Army. During the transition period, from 1989 through 1993, the Army must have soldiers prepared to install and support the new MSE as well as all equipment in the current inventory. This presents a sizable training challenge for not only the active Army but also for such units as the Army Reserve and National Guard.

The rapid prototyping method was used on this project to accomplish a variety of goals. First, a simulation/scenario prototype was designed to show training system managers and General officers what an intelligent tutoring system for MSE might look like. Using the development environment afforded on the Apple MacIntosh with Supercard™, the development team was able to build a MSE simulation with less than a person-month effort. This system is called Advanced Learning for MSE (ALM) because it is designed to provide recurrent training and practice to personnel who have received an introductory MSE course. The prototype was instrumental for making the plan to develop a completed system. The prototype permitted the customer to see what was being proposed. Therefore, they had a concrete idea of what the finished product would look like.

ALM was transported from the Macintosh-based prototype to a Version 0 of ALM on the Electronic Information Delivery System (EIDS), an 80286 computer that is in abundance in the U.S. Army. This Version 0 is in user acceptance evaluation before the fully operational training system is delivered. The use of prototyping on the ALM research and development has ensured that the finished product will evolve to meet the expectations of the Army customer.

Prototyping for Pilot's Associate Pilot-Vehicle Interface

The pilot-vehicle interface for the pilot's associate (PA-PVI) refers to the human-machine interface between the pilot and the aircraft in an as-yet unbuilt jet fighter aircraft. The architectures and implementations of elements of the system have been described elsewhere (Andes, 1987; Hammer & Geddes, 1987; Howard, Hammer, and & Geddes, 1988; Rouse, Geddes, & Curry, 1987). The research and development of the PA-PVI is part of a larger program to research and develop a distributed intelligent system that will reside in the avionics of the aircraft. This project serves to show the role which rapid prototyping can play when it has been an explicit part of the system design process from its inception.

The general goals of using prototyping in developing the PA-PVI were to affect both system design and system users. The primary stated goal was to convince the sponsors of the feasibility of the technologies and concepts involved. In turn this was expected to lead to greater commitment from the sponsors. The goal with respect to the operators was to develop a positive attitude, some understanding, and willingness to accept new ideas. Other goals were to evaluate system functionality, enhance communication among a geographically distributed development team, and to promote a deeper, shared understanding among developers working on different components of the system.

After an initial architecture for the system had been developed and while the first hardware/software prototype was being developed, an initial prototype evaluation was planned. In this evaluation, two scenario based mission prototypes were developed. One had all system functions, pilot actions, and interface displays described for the PA-PVI. The other had all system functions, pilot actions, and interface displays described for a current jet. These were presented to pilots for comparative performance evaluation and the results are described in Sewell, Geddes, & Rouse (1987).

After this purpose- and function-level prototype evaluation a series of computer-based functional prototypes were developed and presented to sponsors, potential operators, and the complete development team for review. As the system evolved through these prototyping cycles, a low fidelity simulator was brought into the plan. This provided a medium in which to develop form-level prototypes that could be used for systematic evaluation by potential system users. Current plans include redeveloping the system in high fidelity simulations for formal evaluations as a Version 0 prototype.

Rapid prototyping in the PA-PVI has been successful in several respects. Many of the goals have been achieved. Sponsors have demonstrated greater

commitment to the system by asking for continued development past research and initial development. New sponsors have demonstrated commitment by asking for the technology to be applied to other domains. Pilots have begun to demonstrate understanding and acceptance of the system. Some have served in advisory/testing roles and some have moved into research and development jobs to help further development. Developers have been able to use the prototypes for evaluation and as a medium for increased communication.

As a result of integration and evaluation efforts, significant redesign and redevelopment has occurred to date. At the same time, it is only through intense communication that redesigns among the different components could and were brought into compatibility. This also raises the only significant negative effect. Prototype integration was infrequent enough to allow divergence in development. This divergence was sometimes subtle and often required tremendous efforts to reconcile. This could, perhaps, have been avoided through traditional design practices using complete decomposition and design before development; or, through more frequent prototype integration.

Prototyping for Graphical Display Presentation for Maintenance

For maintenance problem-solving the development of graphical displays that can be shown on small computer-based display surfaces as an alternative to blueprint-sized hardcopy is a high priority. Currently, the manuals for maintaining complex systems often make up thousands of pages which must be revised and updated in addition to being used by maintenance technicians in their everyday work. A research and development project to compose and evaluate principles which will drive this display development is currently underway. The early research and development has been reported elsewhere (Sewell, Rouse, & Johnson, 1989). The work will transition to system design and development in future projects. For this paper, this project serves to show how rapid prototyping can play a role even in the most preliminary stages of system development—in this case during early research.

There were two general goals of the prototyping effort involved in this project. One was to affect the system design through the development of principles and displays for evaluation. It was only through prototypes that these could be evaluated. The other was to affect the potential system operators (maintainers) in two ways. One desired effect was to have them accept the researchers in their environment. The other was to have them accept the researchers as having potential to benefit maintenance jobs.

The goal of being accepted by the maintenance technicians was probably the more important goal. It certainly took precedence since achieving all other goals depended on this one being accomplished. The initial response of the

maintainers was to tell the researchers that they "already had what they needed", they "had previous, failed attempts sitting unused at their work site", and so forth. In response, the researchers developed prototype computer-based graphical displays to demonstrate some of the possibilities of their approach. Based partially on this prototype, the maintainers enthusiastically consented to participate in the research.

The goal of affecting system design by developing principles from which to generate elements of a new system that is a complete departure from existing maintenance systems is a lofty goal. Unfortunately, it is one that the maintainers find difficult to relate to. They are forced to work with what they have and have little time to devote to exploring underlying issues. Yet, it is necessary to extract information from the maintainers in the form of existing knowledge and feedback on ideas that are generated. Since these maintainers find it difficult to evaluate the new ideas in the form of purposes, requirements, and principles, researchers must develop concrete examples embodying those purposes and principles.

The researchers generated paper-based sets of prototype displays (sized for computer screens) from initial requirements and principles. These displays were then used by the maintainers as they talked through solving a maintenance diagnosis problem. For each prototype display the maintainer was probed for underlying reasons why it was good or bad for the maintainer's activity. The results from these sessions provided much information that was used in the continued development of display principles.

In addition to changes in the design ideas, the researchers were seeking to increase the maintainers' confidence that a system could be built eventually and to generate realistic expectations about what kind of system might be built. This was much more difficult and only met with mixed sessions. The maintainers held strong opinions about possible technology, about the complexity of their work, and about the capabilities of non-maintainers. These opinions were generally negative with respect to the future of the desired system development. By the end of the current research, these maintainers felt positive about the capabilities of the researchers and the prospect of developing useful materials. However, they still felt negative about the technology required for such an effort and about the prospect that the current work would eventually be turned over to other designers/developers who were not acceptable to the maintainers.

As a result of this early prototyping and research effort, the designers and the users appear to have moved closer to a common view of what might be developed to support the maintainers even though they still differ on the feasibility of such a system. Future efforts in the research will be to develop

computer-based prototype implementations of principle-driven displays for experimentation. These should also provide the opportunity for further impact on future design concepts and to make inroads with the maintainers to show that the technology is feasible.

Conclusion

Prototyping is a design, development, and evaluation process that creates hardware or software models that represent current conceptualization of the products in design. We have defined prototyping by its goals, kinds, and behavioral effects. In addition, we have presented specific application examples examined in the framework provided by the definition.

The most important elements are the extensions of prototyping to consider explicitly the behavior of the different participants in the system-design process and the impact of prototyping on that behavior. After all, the evaluation and fate of any newly developed system is determined, not solely by the characteristics and qualities of the system, but also by the behavior that system users demonstrate toward the system. To define those behaviors and the factors that affect them is to make them available for manipulation. Future system developers should take into account these potential effects when planning prototyping activities.

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Natural Language Interfaces

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ABSTRACT

Following an introductory review of natural language processing activities and analysis technologies, natural language *interfaces* are defined and their advantages, disadvantages, and desirable features are discussed. Four major clusters of natural language interfaces are identified: Query, Conversion, Commentaries, and Control. A number of different examples of these clusters are presented and discussed from the viewpoints of cognitive and computer processing. Finally, four examples of remaining frontiers for practical natural language interface applications are presented and discussed.

Introduction

A somewhat broader perspective on natural language interfaces is taken in this review than the customary view that natural language interfaces are primarily input-communication channels to the computer, speech recognition being the most cogent example. This view takes any natural language processing activity supported by the computer as being a candidate *interface* activity depending primarily on what processing is accomplished by the computer and how quickly. Thus, today's "batch-processing" language applications could well be tomorrow's interfaces given appropriate changes in technological implementation. For example, we don't ordinarily think of translation of large texts from a foreign language into English as an "interface" application. However, if the translation were to be accomplished quickly and surely enough to support an English-speaking-only user's random hyper-text browsing of foreign texts in a seamless immediate fashion, we would surely view the activity to be a natural language interface one. Given the extraordinary advances of computer performance on the one hand, and the enormous advances in computational linguistics on the other, such a transition is quite conceivable.

Adopting this orientation we then devote careful attention to a wide variety of human-computer activities involving natural language—briefly emphasizing speech recognition. We focus on the differences between natural and non-natural languages and the nature of the various types of computational tech-

nologies involved in processing natural languages. The scene having been set, we then define a subset of natural language applications as being *interfaces,* and these provide the context for the remainder of the paper.

Natural Language Interfaces, at the present imperfect state of technology capability, have a number of disadvantages to offset their obvious, and not so obvious, advantageous features, and we appropriately dwell on both of these.

Given a Natural Language Interface, we consider how we might evaluate its effectiveness, particularly its cognitive adequacy, by enumerating and reviewing an extended set of desirable features.

Within all of the above context we then identify a set of four clusters of possible and actual natural language interactive interface activities, as characterized by their input-output characteristics. We provide a number of examples of these, focusing on a few, including that set which combines natural language with non-language gesturing actions.

We conclude the review with a proposal for several new types of practical natural language interfaces whose development would provide great practical advantages.

Types of Natural Language Applications

Types of Natural Language Input/Output Applications

Almost all computer processing applications involving natural language are concerned with language as either input or output (the alternative being to employ language forms for internal reasoning activity independent of I/O). For language as *input,* the applications differ as to ultimate function but all involve the analysis at various levels of the natural-form input.

In Table 1 are listed 8 examples of areas involving input-language analysis. There has been some interest in using particularly voice input in command situations, such as of industrial robots. Analysis of natural language software requirements and designs, expressed as text, has occasionally been raised as a possibility, but there has been little computational work. Analysis of meta-level queries, such as "what do you know about", have also been cited, but the extensive query work involves analysis of specific concrete queries. Some knowledge acquisition work exists in which users enter simple natural language assertions about properties of entities and entity-relations. There continue to be an increase in the number of programs which provide analysis of stylistic characteristics, and to a lesser degree the thematic and other content, but there is very little work attempting to provide deep analyses of substantial coherent text.

Concerning the 11 types of natural language output generation also listed

Table 1.—Human and Computer Activities Using Natural Language (NL) Processes

NL Process	Activities	Extent of Computer Research
NL Input Analysis	Command Following	Some
	Software Design/Programming	Little
	DB Query Analysis	Extensive
	Meta-level Query Analysis	Little
	Single Assertion Comprehension	Some
	Style Analysis	Extensive
	Content/Theme Analysis	Some
	Deep Understanding of Coherent Discourse	Very Little
NL Output Generation	Status Informing (speech)	Some
	Instruction Generation	Little
	Response to Query	Some
	Conversational Response	Some
	Report Generation (from DBs, etc.)	Moderate
	Abstracts, Synopses, Paraphrases	Little
	Language Translation	Extensive
	Sketchy stories, plans, etc.	Little
	Short Explanations	Little
	Extended Reasoning	Very Little
	Large, creative, coherent productions (e.g., novels, instruction manuals, position papers)	None

in Table 1, some work involves synthesized speech status reports or directions, and text query responses, and conversational output, but most of the output work has been concerned with bulk text translation. Aside from some database-driven report generation, there has been little study of other forms of output and essentially none concerning large creative productions.

Only some of the applications listed in Table 1 would today be considered as involving natural language *interfaces* but we argue later that all of these are potential candidates in the future, given suitable technological improvements.

Physical Characteristics of Natural Language Input/Output

When natural language is input or output by human or computer it has a variety of physical characteristics as described in Table 2. For example, the generic input activity of *reading* involves some type of natural alphabet orthography when presented to humans and some form of digital encoding standard for computers. The acquisition of computer-readable text is typically accomplished by human transcription, used various word-processing or text-processing software packages. However, more and more capability is being provided by acquisition directly from physical text via scanning devices coupled with Optical Character Recognition (OCR) capability. The computer activity comparable to human listening is that of speech recognition which involves processing of digitized speech samples either represented as time-varying signal waveforms or as Fourier-transforms of power vs. signal frequencies.

Table 2.—Basic Natural Language Input/Output Processes and Their Associated Signal

	Signal Characteristics		
I/O Process	Human	Computer-Equivalent Representation	Computer Activity Known As
Input[1]			
Reading	Natural-alphabet orthography	ASCII/EBCDIC codes	Text processing
Listening	Complex speech, frequency range ~100–2000 Hz.	Digitized speech samples and their transformations	Speech recognition
Output[2]			
Writing	Printed, scripted, typed orthography	ASCII/EBCDIC	Text generation
Speaking	Speech utterances	Digitized synthesized speech	Speech synthesis

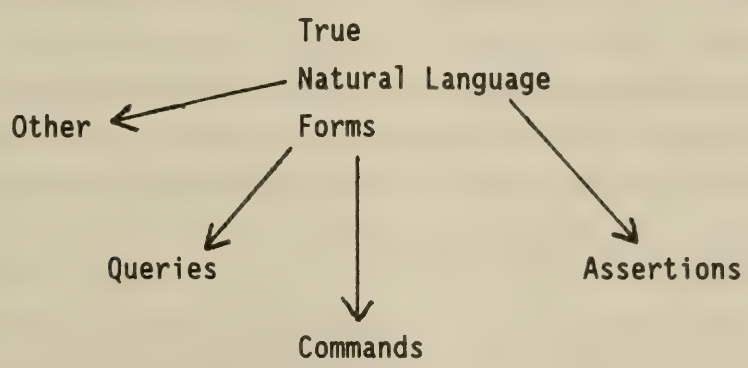
[1]Because the vast majority of study and development is on the input in the table, we exclude from consideration such other legitimate input processes as braille-reading, interpretation of signed gestures, etc.
[2]For the same reason we do not consider signing and other types of non-standard output.

Human language communication involves a variety of other types of signal encodings besides those listed, including use of sign-language, representation of text as braille, and generation of special coded signals involving such devices as radio morse-code and signal lanterns and flags. Aside from signing, these forms involve relatively uninteresting non-linguistic transformations. On the other hand, the interpretation of signed gestures produced by a human (or the generation of understandable animated signing output) provides a variety of so-far unstudied provocative challenges: recognition of the properties and relations of spatially-separated entities established during sign discourse, characterization of signing in terms of a grammar of signs, elucidation of the signing mechanisms corresponding to the complex features of natural discourse (e.g., topicalization, passivication, "lexical" collocation, anaphora, etc.), etc.

Natural Languages vs. Non-Natural Languages

The discussion of signing provides an introduction into the issue of what is, and what is not, a "natural" language. For the purposes of this paper a natural language is one (1) which is commonly and long-accepted as a language of communication of a human culture in its every-day activities, (2) involving an established orthographic representation of spoken utterances composed from a base alphabet of symbols, and (3) for which there is no evidence of its having been artificially devised or created. Such a definition removes from consideration for the moment such potential candidates as whale language, communications from primates, and even human signing itself. What remains are the unequivocal languages such as English, Russian, Latin, Spanish, etc., and we will simply side-step issues such as the status of dialects, pidgins, and creoles.

With respect to computer processing of language, there are 3 categories of language and non-language that have been considered, as represented in Figure 1. The first is true natural language. Second is a layer of natural languages which are constrained in more significant ways than just by vocabulary restrictions (prohibiting relative clauses, for example) or an artificial language claimed by its proponents to have all the features of the natural model (e.g., Esperanto). These layer languages, which are not considered truly natural here, do however cover most of the important forms of natural language. Finally, there are a variety of non-natural languages which have been partic-



PSEUDO LANGUAGES AND CONSTRAINED NATURAL LANGUAGES

QUERIES	COMMANDS	ASSERTIONS
o Natural-Like Query Languages	o Robotics Languages	o Knowledge Base Formalisms
o 4GLs	o Procedural Programming Languages	o Logic Programming Languages
o (SQL)	o SQL	o Logics (e.g., First-Order) Algebras, Calculi

NON-NATURAL LANGUAGES

Fig. 1. Examples of non-natural high-level computer-input specification languages corresponding to three natural language forms of queries, commands, and assertions. A layer of pseudo natural languages (e.g., Esperanto) and constrained natural languages separates the natural from the non-natural languages.

ularly developed for one or another type of form: query, command, or assertion.

An important characteristic that all of the languages shown in Figure 1 possess in common is the requirement that the input must undergo various levels of linguistic analysis in order to be utilized in the ultimate application of providing data to respond to a query, issuing a machine motor-control instruction, or correctly capturing and representing some kind of knowledge assertion. Such analysis is discussed in the next major section on Technologies, but it can be said that all require a grammar of at least **context-free** power (in the 4-level range from regular, to context-free, to context-sensitive, to Turing-Machine). Where natural language differs primarily from the others in this grammatical regard is in terms of the diversity of acceptable parse-tree structures, relating to the much more flexible set of allowable variations in the surface input than is acceptable to non-natural languages.

Natural Language Speech Recognition

In this general section on natural language applications it is appropriate to focus briefly on the now venerable task of getting computers to recognize human speech. This is probably the most popularized of all the natural language interface applications, and it has reached a stage of impressive maturity in the past five years.

Key to understanding the difficulties of speech recognition and the recent progress is an appreciation for the three first-order variables used to classify speech systems: (1) whether the system handles discrete vs. continuous speech, (2) whether the system is speaker-dependent or -independent, and (3) whether the recognized vocabulary is relatively small (e.g., <2,000 words) or large (e.g., >10,000 words). Five to ten years ago there was still quite active research in speech systems at the lowest end—handling only discrete speech (speech with speaker-inserted pauses between words), for small vocabularies, and requiring special training for each new speaker/user (speaker dependence). Today, hardware boards to accomplish that level of recognition are routinely available from several manufacturers for a few thousand dollars.

Today's R&D speech systems are focused on the high-end of all these variables: speaker independence, large (to very large) vocabularies, and unrestricted continuous speech format. In contrast to the past, most of today's promising systems place heavy emphasis for the determination of speech input on language technologies, particularly phonetic-alphabet grammars employing dictionary look-up and natural language word-string parsers. In Table 3 are listed some of the speech recognition systems under development which fit the above characteristics. Of these, some efforts so emphasize the natural

Table 3.—Selected Speech Processing Systems

System	Where	Purpose	Features[1]	Reference
Sphinx	CMU	Speech Recog.	Cont, SI, LV	Lee, 1989
Pundit	Unisys	NL Parser	NP emphasis	Dowding & Hirschman, 1987
SUMMIT	MIT	Speech Recog.	Viterbi Search	Zue *et al.*, 1989a, b
DECIPHER	SRI	Speech Recog.	Cont., SI, LV, Pr	Murveit *et al.*, 1989
TINA	MIT	NL Parser	Best-first search	Seneff, 1989
MINDS	CMU	Word Predictor	Context Knowledge	Young, 1989
BYBLOS	BBN	Speech Recog.	Context-dependent	Chow *et al.*, 1987
HARC	BBN	Speech Recog.	Chart parser, semantics	Boisen *et al.*, 1989

[1]Cont = continuous speech input, SI = speaker-independent, LV = large vocubulary, >10K words, NP = noun-phase, Pr = probabilistic

language parsing aspects of guiding the recognition systems that a great deal of the effort may be spent on just these aspects; examples are Unisys' **Pundit** and MIT's **TINA**. A key research question for these systems is how to conduct the lexical-search and parsing such that useful results are obtained in real-time to help confirm or redirect the ongoing hypotheses of the front-end audio analyzer components.

While no robust full-function commercial speaker-independent continuous-speech large-vocabulary systems are yet available, there is considerable reason to suspect that yet another five years will see their presence as flexible input interfaces for a host of practical applications.

Natural Language Technologies

We are accustomed to characterizing many "hard" application areas in terms of the variety of technologies that underlay and make possible the achievement of the application functions. For example, for the area of Advanced Manufacturing (flexible manufacturing systems, automated assembly cells, etc.) the key technologies include numerically-controlled machines, Computer-Aided Design software, Computer-Integrated-Manufacturing control packages, etc. However unfamiliar it may be, it is equally appropriate to characterize natural language processing applications in terms of the language "technologies" which underlay them.

We provide this characterization for the first of the two types of natural language applications portrayed in Table 1, the *analysis* of natural language input.

Description of Language Technologies

We show in Table 4 five types of language technologies which can be (simplistically) thought of as applying successively to transform the original lan-

Table 4.—Levels of Natural Language Input Analysis

Processing Level	Unit of Analysis	Major Activities	Output	Example ("Take a chair")
Lexical	Word	Segmentation, affix-stripping, inflectional analysis, lookup	Data records(s): Part-of-speech (POS) person, number, tense, . . .	*take:* vb, pres, sing *take:* n, sing.
Syntactic	Phrase/Sentence	Parsing: POS assignment government, binding, constraint-checking, SVO case-assignment	Parse-tree(s), problem-report	SENT VERB DIROBJ take NP ART N a chair
Semantic	Parse-tree, annotations	Scoping, Quantification, sense-selection, predicate-formation	Logical form	take1 (P1, IMP, ?you, Chair, ?dest)
Discourse	Logical form, Discourse context	Anaphora resolution, argument-filling, sentence fragment coordination	Variable substitution in logical form, additional predicates	(Previous: "Jim, let's play cards. .") ?you = Jim ?dest = in (Liv. Rm.)
Pragmatic	Discourse Representation, goal information, real world knowledge	Hypothesize, goals, intentions, beliefs	Augmented logical form	goal (P1, provide ___ seating), intended ___act (play4), believe (speaker, Jim, X) X = want (Jim, play4)

guage input into a fully-analyzed pragmatically-understood form. We arbitrarily assume that the initial technology of *lexical processing* begins with a preprocessed string of segmented tokens each of which, under ideal conditions, represents either a word or a punctuation symbol (in practice the tokenizer process may well have to interact with the lexical process to achieve this). The purpose of lexical processing is to develop a data-record for each word that contains the feature information needed by the syntactic processing which follows. In the Table 4 example of "Take a chair", the lexical analyzer will typically report features for all of the different parts-of-speech it can assign to each word; for "take" both a verb and a noun part-of-speech are identified, along with some respective features. Perhaps the most important of the lexical processing activities (a sub-technology in its own right) is the stripping of affixes (prefixes and suffixes) until a remaining stem is discovered (e.g., the stem "establish" in "antidisestablishmentarianism").

The beginning stage of *syntactic analysis* is a string of word records primarily characterized by their part(s) of speech. These parts of speech are represented

as so-called **terminals** in a grammar of rewrite rules which specify how these terminals can be combined into larger linguistic units (non-terminals, like **noun-phrase** and **prepositional phrase**). The desired output of the syntactic analyzer is that **parse-tree** which most appropriately describes the grammatical governing and binding characteristics of the part-of-speech elements; in the example, "take" is recognized as a verb, not a noun, with the direct object of its imperative form being the noun-phrase "a chair."

Whereas the actual words and their meaning are of secondary importance in syntactic processing, in *semantic processing* the word meanings become critically important. Suppose that the context for the example sentence "Take a chair" is a social evening in a home, with two couples getting ready to play cards by setting up a card table in the living room and gathering chairs for it from the dining room, and the host—pointing to a particular chair—utters the request with the clear idea that the visitor is to transport it into the living room. Thus, of the many identifiable senses for the verb **to take,** the one of **transporting** is intended (not the one of "behold!" or "consider", for example, or of "deduct" as in "take 5 away from 17 . . ."). This sense may be represented as **take1,** and it can be represented as being associated with additional pieces of information concerning (1) an identification of this unique proposition, say "P1"; (2) who the addressee is in "(You) take the chair", represented by **?you;** (3) what the object of taking is, **Chair;** and (4) what the destination is of this action, **?dest.** These are the "arguments" or parameters that need to be filled in for the take1 sense of "take" in our supposed processing system (another processing system might want fewer arguments, eliminating "?you" or possibly even more, adding one for the speaker). Semantic processing typically arrives at an estimate of the underlying word-sense for words in the utterance by consulting the **semantic-forms**—often called **case-frames**—associated with a dictionary entry, and comparing the constraints for the various arguments to elements in the utterance; for example, if a case-frame direct object is supposed to be an inanimate thing, as with **take1,** then "chair"—being inanimate—fulfills that restriction and the **take1** sense is still a possibility.

The next technology, *discourse processing,* brings in consideration of the preceding text or dialogue to add more information to the semantic logical form by determining things like pronoun referents (there are 3 in "He gave it to him")—anaphora resolution—helping resolve some of the unknown arguments in the logical form (?you and ?dest), deciding what the topic and focus are in the input, checking for clues which reveal the speaker (or hearer) attitudes or argument structure, resolving so-called **cohesion** mechanisms which link parts of the input together, and so forth. Thus, the previous dialogue

might have included the host saying "Jim, let's play cards . . ." with a subsequent reference to the living room, and processing of this previous discourse could resolve the values for the missing arguments in the semantic logical form.

Finally, the last stage of natural language input analysis involves the technology of *pragmatics*—attributing to the agents involved in the language interaction various goals, beliefs, intentions, and plans. Up to this point the focus has been on *what* is being said; here the emphasis is on *why*. Our sophisticated pragmatics processor might thus conclude that the *goal* of the stated imperative proposition P1 is to provide seating, where the intended action is a particular type of "playing", **play4;** and the pragmatics processor further concludes that the speaker of "Take a chair" believes that Jim wants to engage in **play4.**

The maturity and competence of these five technologies is highest with the lexical and syntactic processing and falls off markedly after semantics. With respect to non-natural languages, no differentiation is made among the last 3 technologies, nor are the semantics—in the sense of constraints on arguments—often made explicit in formal defining assertions; the constraints are usually implicit in the procedural compiler code.

Very large dictionaries of simple word strings are now very common because of the interest in PC-level spelling checkers, but full dictionaries with extended word-features for multiple senses, and senses represented as case-frames with selectional constraints, are also becoming more available, at least in research settings—for other languages in addition to English (cf. Byrd, *et al,* 1987). The trend is very much towards putting more and more information in the dictionary, particularly in contrast to representing the same information in the form of grammatical or other rules; some syntactic approaches very much rely on this strategy (e.g., Lexical Functional Grammer; Kasper, 1987).

While there is considerable agreement among computational linguists concerning desirable dictionary features, there is much less agreement concerning how the syntactic processing should be accomplished. In the early days of parsing, there were basically two approaches: *bottom-up* assembly of part-of-speech terminals into phrases, and these into clauses (e.g., phrase structure grammars; cf. Heidorn *et al.*, 1982), and *top-down* hypothesization of high-level clauses or phrases decomposed down into parts-of-speech (e.g., Augmented Transition Networks; Woods, 1980). Today, given the wide variety of natural language applications being studied, there is a great diversity of grammar approaches and formalisms, each having particularly useful properties for its intended span of applications. Table 5 lists some of these approaches which may be very briefly sampled: Government and Binding Grammar is proving

Table 5.—Some Popular Grammar/Parser Formalisms and Approaches

Grammar	Reference
Government and Binding Grammar (GB)	Berwick & Weinberg, 1984
Lexical Functional Grammar (LFG)	Kasper, 1987
Tree Adjoining Grammar (TAG)	Joshi, 1987
Augmented Phrase Structure Grammar (APSG)	Heidorn *et al.*, 1982
Augmented Transition Networks (ATN)	Woods, 1980
Categorical Grammar	Pareschi, 1988
Head-Driven Phrase Structure Grammar (HPSG)	Maeda *et al.*, 1988
Chart Parser	Allen, 1987
Definite Clause Grammar (DCG)	Pereira & Warren, 1980
String Grammar/Functional Grammar	Sager, 1981
Functional Unification Grammar (FUG)	Kay, 1985
Modular Logic Grammar (MLG)	McCord, 1985

to be particularly useful in our BRIDGE Tutor project for multi-language training of Army interrogators (cf. Berwick & Weinberg, 1984); the bottom-up Augmented Phrase Structure Grammar was very useful for the EPISTLE text-critiquing project (cf. Heidorn *et al.*, 1982); and Modular Logic Grammar is proving to be an effective approach for language translation (cf. McCord, 1985).

Syntactic processing and the other language technologies discussed are pervasive throughout all types of natural language applications, not just analysis of input. However, there are additional technologies that apply more to output generation that are also identifiable in the research literature. For example, the process of *planning* a discourse or text involves very complicated consideration of the goals balanced against the nature of the audience, the time and resources available, etc. At the end of this planning process are the detailed decisions concerning what actual words to use, how much information to give in one versus multiple sentences, etc. A related not entirely subsidiary process is establishing *cohesion* between the next planned output and the previous discourse as well as the discourse environment. As our understanding of these processes matures, and as they are better able to be represented in software, then it is likely that they will emerge, like dictionary and syntax, to be full-fledged additions to the arsenal of linguistic technologies.

Interaction of Technologies with Application Effectiveness

An illustration of how the language technologies work together and how one gains additional application capability as they are added on is given by the Table 6 example of text-critiquing for various kinds of spelling, grammar, and stylistic errors (see Miller, 1990). Considering spelling errors, certain of these need only a dictionary look-up to determine that they are wrong—as with "myne" for example, which is clearly not a word. However, when the

Table 6.—Types of language technology needed to detect 3 different classes of text-production errors

	Language Technology		
Text Errors	Dictionary	Syntax	Semantics
Spelling	"This is *myne.*"	"Don't press *to* hard.	"The pipe collapsed due to *mental* fatigue."
Grammar	"He *ain't* happy."	"The *purpose* of these meetings *are* . . ."	"The age of these men *which* are unmarried."
Style	"Our arrangement has now been *finalized.*"	"He who has not knows what he who *has possesses.*"	"*Coming* around the corner, the *building* shone red in the sunset."

substituted word is also a word—as in "Don't press to hard"—dictionary technology alone is insufficient to detect the error; syntactic analysis is needed to reveal that "to" and "hard" can't be put together to form a prepositional phrase or an infinitive or any other acceptable construction. In the third example concerning "mental fatigue" (instead of "metal fatigue") both dictionary and syntax are necessary but insufficient to detect a problem; semantics really are necessary to determine that **mental fatigue** doesn't apply to pipes!

In general, improvements in one technology can compensate for deficiencies in others, and one is often able to solve a difficult application problem by bringing to bear various aspects of several technologies, not just the one that seems most to apply. Thus, for example, ways of handling certain kinds of complex grammatical constructions have been developed by putting additional information into the dictionary or increasing the power of the semantic component.

Natural Language Interfaces: Considerations

We are finally prepared to deal with the main topic of the paper, having laid the necessary groundwork in terms of applications and technologies. In this section we deal with various considerations of Natural Language Interfaces (NLI), leaving to the next the discussion of specific examples.

Definition of NLI

NLI have two forms of realization, input and output, and we propose the following definition to cover both:

> "Natural Language Interfaces are communication channels between human users and computer systems and involve the dynamic processing of coherent natural language, either as analyzed input or as generated output, with sufficient speed and accuracy to support an interactive task."

Essential phrases are those of *communication channels* (to insure that the language has a key input or output role), *dynamic* (to eliminate pre-planned or canned processing), *coherent* (to indicate the requirement to guide processing via a larger language context), *natural language* (to indicate the need for language technologies and exclude artificial "languages"), and *interactive* (to eliminate one-shot or batch-type applications). Thus, translation of a speaker's typed input from English into French text is an example of NLI if it occurs rapidly, such that it could be dynamically reviewed by the user (or read by a Parisian and replied to), and it isn't if the translation is delayed until all the text is input and then translated at some later time.

Advantages of NLI

NLI are usually touted for the fact that users don't have to learn them, as shown by the initial advantage entries in Table 7. Less frequently mentioned is that fact that, along with the language itself, come mechanisms for *using* the language that are extraordinarily adaptive and productive. A person, looking at a drawing of an unfamiliar mechanism, has several well-established strategies for generating acceptable *names* of parts of the mechanism for use in discussion; and has well-used strategems for generating descriptions of the mechanism's operation or formulating queries. There are, in addition, a half-dozen or more specific natural language mechanisms for referring to things—e.g., extrinsically ("that one over there, third from the left"), anaphorically to prior dialogue ("she didn't know whether she had said that, but *that* wasn't the point . . ."), and even cataphorically to dialogue yet to come ("The points I want to make are these three: . . .").

Table 7.—Advantages and Disadvantages of Natural Language Interfaces

Advantages	Disadvantages
• Naturalness, cognitively not demanding • Highly Portable • No learning required • Easily remembered • Flexible, adaptive to a host of situations • Thus, very big reusability • Easily productive for new requirements (naming, new procedures) • Extraordinary facilities for reference (and indexing) and description • Provides (esp. via semantics) for all desirable features of ideal programming languages—information-hiding, data abstraction, operator overload, feature inheritance, each entity with its own methods, etc.	• Verbosity is tiring for experienced users • Ambiguity is always a problem (sense, reference, figurativeness, scope, quantification, attachment, goal . . .) • Presupposed, entailed, and implied general knowledge is so great • Subtleties of speaker's attitude as expressed in the utterance/text can't yet be appreciated • Users don't have analytic knowledge of language processing to help computer out • Ellipsis, fragments and ill-formed but (human) comprehensible input cause difficulty • User's high expectations of computer's capability can't be met • Expertise needed to develop and maintain NL system is not readily available

Other advantages accrue from the same reasoning used in the field of software engineering to argue for one programming language or methodology over another. Thus, natural language is as reusable as things get, and all of the special features of object-based and object-oriented methodologies so popular these days have their cognates in natural language features.

Disadvantages of NLI

On the other hand, non-enthusiasts will point at a number of supposed problems with natural language, particular as input. These points are well taken with respect perhaps to *existing* NLI implementations, but most of them would lose their force were the analytic capability of the computer to be substantially improved. Thus, it is certainly true that natural language can be verbose if the input analyzer doesn't support all the normal ways that natural language provides for terse rapid communication—if it can't handle ellipsis and fragments, doesn't handle relative referencing and indexing, and has little semantic/pragmatic capability to resolve the meaning from the context. Similarly, ambiguity can occur in a variety of forms and can be truly debilitating if the processor is primitive in its capability to handle it.

More fundamental is the fact that people typically have little appreciation for what is and is not difficult to process, and they will be of little help in assisting the computer in resolving their input unless the problem is stated just right. Similarly, people often overcome communication difficulties via their vast shared knowledge about the world, and it's unlikely that this aspect of NLI will approach this capability for many years; this in turn contributes to users' being frustrated with what the computer can do vs. what they expect it to be able to do.

Concerning the subtleties of engaging in conversation, taking turns, detecting key attitudes towards the discussion topics, and identifying communication problems, etc., there is a great deal of progress on all of these issues towards finding ways of formalizing them in software, such that these aspects can be imagined to be well-supported in future systems.

The general solution to the problems of using NLI, then, is to improve their processing sophistication and capability; there appear to be few truly inherent disadvantages of natural language when it is implemented in its full range of mechanisms. Given the progress in all of the language technologies, this approach appears to be genuinely feasible within the next decade.

Desirable Features of NLI

Having decided in favor of NLI, what then should one look for or insist upon? Here one must take into account general psychological principles as

well as specific knowledge concerning language-use. We provide some 14 criteria in Table 8 for evaluating NLI, and we indicate our evaluation of their progress to date. These desiderata are listed roughly in order of decreasing priority, from the point of view of insuring the most support to the widest set of NLI applications.

First on the list is *robustness*. Every human editor appreciates how difficult it is to eradicate every last ungrammaticality, typo, punctuation error, not to mention the more serious problems of non-sequiturs, poor organization, uneven content, etc. NLI systems must be able to handle the ill-formed input of all kinds that is certain to occur, if only to come back with clarification requests, just like people do all the time.

Next on the list are good coverage by all the language technologies. NLI with toy vocabularies, skeletal grammars, and inadequate higher processing cause the greatest frustration and provide poor application support because of inadequacies and errors. Although off-the-shelf computer dictionaries and grammars are not yet common, there is today a much higher incidence of reusability of language technologies than ever before, and coverage problems will certainly become more tractable.

Table 8.—Desirable Features of Natural Language Interfaces

Desirable Feature	Explanation	General Status[1]
Robustness	Can do its job despite ungrammaticalities, misspellings, punctuation errors, etc.	3
Good Word Cover	Vocabulary is completely sufficient.	3
Good Grammar Cover	Deals with wide variety of grammatical constructs.	3
Good Semantics Cover	Develops acceptable meaning interpretations.	2
Good Pragmatic Interpretation	Recognizes intended meaning and purpose.	1
Graceful Failure	Doesn't just quit, provides information on its difficulties, suggests alternatives.	2
Explanation Facility	Gives the user and the developer some kind of trace or explanation capability.	2
Handles Ellipsis/ Anaphora	Accepts (syntactically) incomplete but contextually comprehensible input. Correctly interprets referring expressions.	3
Reasonably Extensible	Most importantly its vocabulary can be added to with modest difficulty.	3
Input Facilitation	Uses variety of means to ease input, such as "auto-completion" of previously used words based on first few letters.	2
Problem Detection	Sensitive to user difficulties or, especially, misunderstandings.	1
Paraphrase Production	Can produce pragmatic equivalent to an expression to aid user understanding.	2
Supports Extended Dialogue	System can engage in a "conversation" with user, lasting a number of turns, making the appropriate integrations and inferences.	2
Supports Multi-Modal Input	Integrates natural language text (or speech) input with gestures, eye movements, etc.	2

[1]Status codes are on a 5-point scale from 1 = very little progress to 3 = substantial progress to 5 = problem essentially solved.

The next two points, graceful failure and explanation facility—and also paraphrase production—provide the user with some insight when difficulties are encountered, something they are more and more accustomed to in most of the non-NLI computer applications. A related, and more difficult capability, is to monitor user performance for problems in the use of the NLI and provide feedback.

The handling (and production) of language fragments is essential to supporting fast-moving dialogue, as is the capability to handle all the varieties of referencing, whether via pronominal anaphora, definite noun phrases, or deictics ("this, that").

A lot more could be done to permit users to add capability to NLI systems, particularly vocabulary. Similarly, for typed input, greater facilities can be provided to reduce the amount of typing required. One useful technique is to have the system automatically complete the input with words it knows given the first few input characters, changing the candidate as necessary with each new character input.

The final criteria provide extensions of the interface both in terms of time/coverage, for dialogue support, and also in terms of modality, to incorporate information from gestures and eye movements in particular to be used as referring sources.

Natural Language Interfaces: Types and Examples

Four general classes of NLI can be identified, as shown in Figure 2. **Query NLI** typically involve a typed-text question augmented in some cases with information from a gesture or eye-movement. The response is primarily information from a database. **Conversion NLI** involve the mapping of input into some transformed type of output, either a shift in modality from speech to text (or vice versa) or a translation within the same modality (only text, so far) from one natural language to another. **Commentary NLI** have a much broader input capability, taking in almost any object for examination and then providing some natural language reaction to it—comments, critiques, annotations, summaries, or brief reports. Finally, **Control NLI** use natural language speech or text commands to control the computer system, applications, or some attached robot or mechanical operation. Examples of these types of NLI are shown in Table 9 (pure speech recognition systems were presented in Table 3).

The table examples are really just a sampling of a much larger set of NLI which are undergoing substantial development, not to mention the numerous additional 1–2 person university projects. A decade ago a listing of *all* systems, including 1-person projects, would have hardly filled the page. This is due

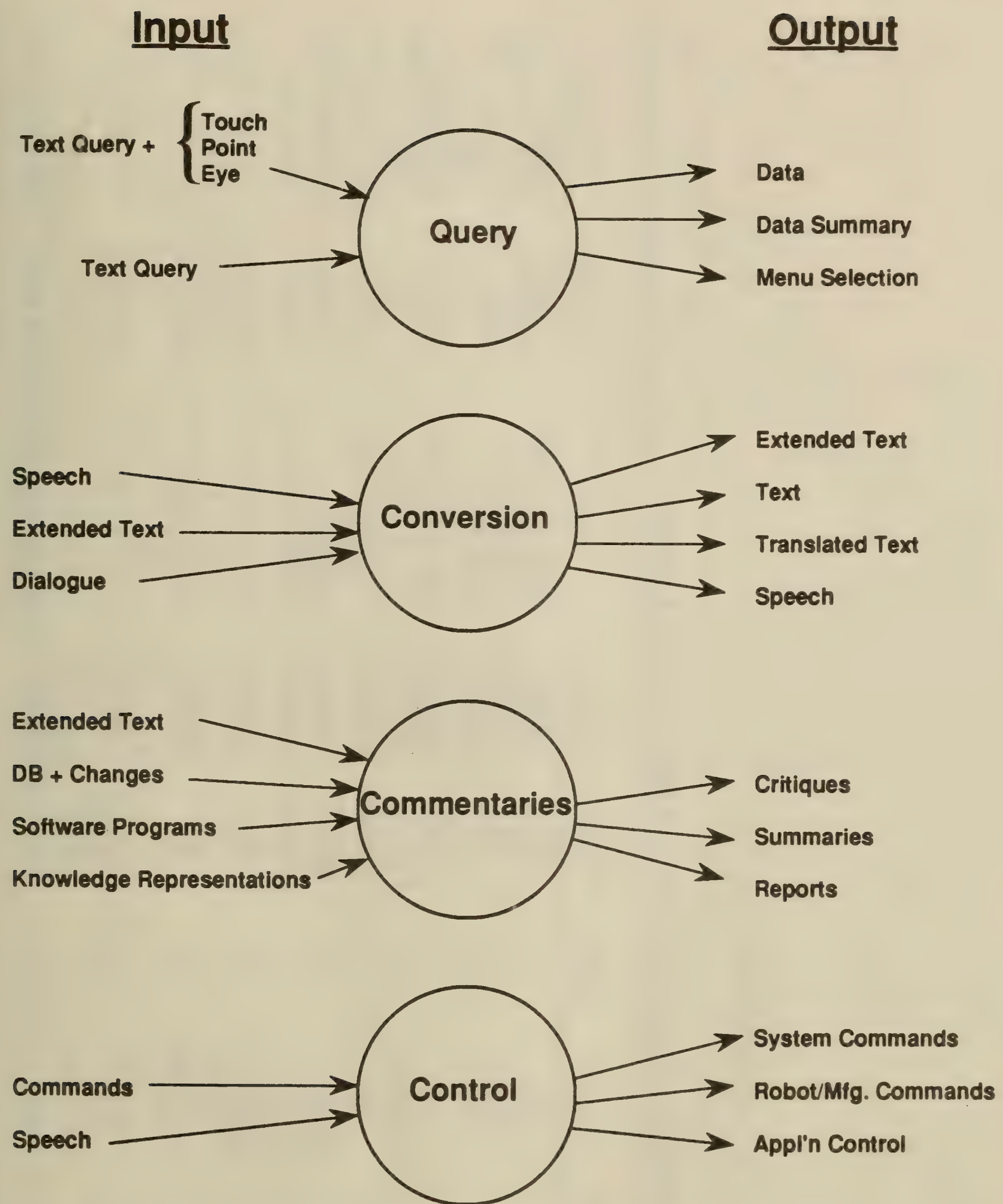


Fig. 2. Four Clusters of Natural Language Interactive Interface Activities

partly to the broad expansion of effort in the NLI arena in this time period. It is also due to the improvement in computer software efficiency and hardware speed such that these applications are capable of being truly interactive.

A number of the examples are much richer than they may appear from the tabled descriptions. For example, the *Bridge Tutor* (BridgeT) is being developed to provide second-language support and training for Army interrogators (MOS 97E; Miller, 1990). In the simulation mode, personnel are to type in

Table 9.—Some Natural Language Interface Systems Other than Single-Media Voice Recognition

Input	Parsing Level[1]	Output	Output Processing[2]	Output Information Source[3]	Language I/O	Features	System Name	Reference
Text Query	4	Data	1	DB	English(I)	Categorical Grammer	TELI	Ballard, 1988
Text Query	4	Data	1	DB	English (I)	Logical Form	Natural Lang.	NL Inc., 1986
Text Query	4	Data	1	DB	Japanese(I)	World Model	KID	Ishikawa *et al.*, 1987
Text Query	4	Data	1	DB	English(I)	Robust, Comm'l	Q&A	Hendrix & Walter, 1987
Text Query	2	Data	1	DB	English(I)	Dict.-Driven, Comm.	Intellect	AI Corporation
Voice & Pointing	2	Menu-Selection	1	DB/Pointing	English(I)	VPL DataGlove	(Glove)	Weimer & Ganapathy, 1989
Text Query & Touch	4	Data	1	DB/Touch	English(I)	Resolution Powerful Anaphora	SHOPTALK	Cohen *et al.*, 1989
Text Input & Touch	4	Data Appl. Control	1	DB/Touch	English(I)	Multi-Media Integration	CUBRICON	Neal & Shapiro, 1988
Text Input & Touch	4	Data Appl. Control	1,6	DB/Touch	English(I)	Discourse Model	XTRA	Wahlster, 1989
Voice	3	Real-Time Applications	6	Input	English(I)	Cockpit Applications	Pilot's Associate	
Voice & Eye	2	Tracking	—	Input	English(I)	Control Applications	OASIS	Glenn *et al.*, 1986
LISP Program	—	Multi-Sentence Critique	5	KB	English(O)	Rhetoric Structure Theory, from NIGEL	PENMAN (PEA)	Hovy, 1988a
Conceptual Depend.	—	Multi-Sentence Articles	5	CDs + KB (Topics)	English(O)	Good, Bad, Biases	PAULINE	Hovy, 1988a
DB	—	Multi-Sentence Text	5	DB, KB	English (O) French(O)	Commercial	ORA	Odyssey
Restricted Query	3	Data	1	DB	English(I)	Menu-Selection of Query Elements	NL Menu	Tenant *et al.*, 1983

Table 9.—Some Natural Language Interface Systems Other than Single-Media Voice Recognition (Continued)

Input	Parsing Level[1]	Output	Output Processing[2]	Output Information Source[3]	Language I/O	Features	System Name	Reference
Restricted Query	2	NL Answer	2	Stored Text	English(I/O)	Menu-Selection at All Dialog Points	Advice	Frohlich & Luff, 1989
"NL" Query	1	Hypertext	2	Stored Text (Hypertext)	English(I/O)	Simulates NL Processing	Conversational Hypertext	Whalen & Patrick, 1989
Extended Text	2	Speech	3	Input	English(I/O)	High Quality	Walrus	Klavans *et al.*, 1984
Extended Text	2	Speech	3	Input	English(I/O)	OCR Front-End Commercial	Kurzweil	Kurzweil Products
Extended Text	2	Speech	3	Input	English(I/O)	Bell Labs Developed	Text to Voice	AT&T
Extended Text	4	Critiques	4	Input/ Studies	English(I/O)	Grammar/Style Critique	EPISTLE	Heidorn *et al.*, 1982
Extended Text	4	Text	5	Input	German(I) English(O)	Also Dutch-French German-Spanish	METAL	Slocum, 1988
Extended Text	4	Text	5	Input	Japanese(I) English(O)	Lexical Transfer	Grade	Slocum, 1988 Nagao *et al.*, 1988
Extended Text	4	Text	5	Input	Spanish(I/O) English(O)	Also ENGSPAN	SPANAM	Vasconcellos & Leon, 1988
NL Dialogue	4	NL Dialogue Response	4	KB	German(I/O) (Korean)	Army Interrogator Intelligent Tutor	Bridge Tutor	Miller, 1990
NL Dialogue	4	Translation	4	Input	Eng.-Jap.(I/O)	Toshiba Product	AS-Transac	Amano *et al.*, 1987
Text Command	4	MS-DOS Commands	—	Input/KB	English(I)	Turbo Prolog	NL DOS	Lane, 1977
Text Command /Query	4	HL Answer, Control	4	KB	English (I/O)	Robust Understanding, Robot Assm.	MURPHY	Selfridge, 1986

[1]Input Parsing Level Codes: 1 = Word/Phrase Spotting, 2 = Primarily Lexical Processing, 3 = Constrained to Regular or Context-Free Grammar, 4 = Full Syntactic/Semantic Parsing.

[2]Output Processing Codes: 1 = Data Retrieval, 2 = Text Retrieval, 3 = Pronunciation Transformations, 4 = Generated Phrase/Sent., 5 = Generated Multi-Sentence Response, 6 = Application Control

[3]Output Codes: DB = Database, KB = Knowledge Base

questions they would pose to a detainee, pictured on the display from a videodisc player, according to a particular style of interrogation. The typed input—in German, first, then Korean and Spanish—is passed to a natural language component for analysis. Based upon the correctness and adequacy of the question (as evaluated also by an intelligent "master tutor" component), a typed response or a digital pre-recorded audio output is generated, or else the display can show a puzzled prisoner, not understanding, saying "Bitte?"

The projects which combine natural language input with other modalities—particularly pointing and eye-movements—are also very exciting. These NLI provide a much higher degree of naturalness than with natural language alone, and this also extends to brevity. In Table 10 we identify 7 strategies for referring in natural language to an element on a computer display. The simplest of these is a simple statement like "here" accompanied by a pointing gesture. For natural language alone, especially for relative referencing expressions, the length of the referring phrase—as well as the difficulty in processing it—increases dramatically over the language plus gesture mode. In this combined mode the display coordinates activated by the gesture only need to be coordinated to the "closest" referring expression in the natural language input. Thus, a speech input spread sheet with touch capability could tie data cells to processing instruction via commands like "Change this, this, and this to zeroes", where in association with each "this" was a screen touch onto a displayed data area.

These and the other tabled applications illustrate the health and vigor of NLI development and the opportunity for improved computer-user interface capabilities utilizing natural language facilities.

Remaining NLI Frontiers

We conclude by sketching four types of extensions to existing NLI which could provide particularly useful application functions, as shown in Table 11. The first two are predicated on the assumption that when a user is having difficulty and needs to ask a question, natural language is the most immediate and easiest means of supporting this need. The first, *Meta-level Dialogues,* occur when the user wishes to talk **about** the application itself, not about particular transactions within it. A major difficulty for supporting this extension within an existing NLI is that of recognizing that the user's input is a meta-level comment. Self-references and "you" references to the system may be reliable markers, as may question markers like "why". On the response side, formulating reasonable bounds on the scope of the question and generating an appropriately general response are two major difficulties. Never-

Table 10.—Natural Language Strategies for Referring to Elements on a Computer Display

Strategy	Example of Natural Language Output
Absolute Location (pointing)	"Right here"
Absolute Coordinates	"Fourth line, 12th column", "Map coordinates A13"
Relative Coordinates	"In the second paragraph, third line, 2nd word" "About 2 inches below and left of center"
Labeled Text Target	"The section headed 'Performance' " "Field 12 'Marital Status' "
Relative Text Target	"The first word after 'disengage clutch' " "In the section for 'occupation'; the second question"
Well-formed Graphics Target (for an image/graphic)	"The rear door in the side view drawing" "The third primary input line from the top"
Relative Graphics Target	"The area just above the main entrance" "A point midway between the top of his upper lip and the bottom of his nose."

theless, such a facility would provide users the capability to bypass much descriptive and instructional material and develop the appropriate concept of the system's goals when the need was recognized.

Situated Help refers to the situation in which a user asks for help with respect to a particular problem situation she finds herself in, particularly when available help sources weren't sufficient. We conjecture that the desire to use

Table 11.—Some Remaining Frontiers for Practical Natural Language Interface Applications

Application	Precipitating Condition	Examples
Meta-level Dialogues	User needs to understand systems, goals, intents, overall conceptual structures, and knowledge limitations, etc.	"Why are you asking me this?" "What kinds of things do you know about?" "How am I doing?"
Situated Help	User can't get information she needs from on-line help or from manuals, wants to get assistance for this particular situation	"I can't figure out how to get out here!" "What's wrong with my command—that it isn't being accepted?" "How do I change this back?"
In-Depth Interviewing	System has detailed knowledge-acquisition objectives re an informed human source. System needs to cover a lot of ground in interview resulting in integrated picture, with all contradictory areas followed-up	"How do you know when a pie is done?" "Is bread-baking similar to baking pies?" "I thought you said you can't tell when it's ready just by looking at it."
Extrinsic-Referencing Dialogues	User and system (or robot) share a view of some extrinsic reality (display screen, image, etc.) and are performing cooperative examination or manipulation of it. Need to not only handle individual extrinsic references but coordinate world views.	"I think this doorway here ⟨gesture⟩ is too wide. Make it a bit smaller . . . No, that doesn't look right, put it back like it was." "Pan around to your left. Stop! OK, continue. Wait, go back! "Change the name to 'Smith' throughout. Now move the 1st paragraph to follow the second. Now, in the very first line. . ."

natural language here is very strong, through frustration and the desire to get on with the task. There are several major difficulties for this NLI possibility also, both linguistic and extra-linguistic. The language problems are particularly those of finding the exact referent in the referring expression, especially as this may be a past action, not just an entity. In addition there will probably be the choppy "emotional" style associated with writings in which the author is expressing some kind of upsetment—use of exclamation marks, dashes, ellipsis periods, etc. These will almost certainly not be interpretable. Outside of the language problems there is the reasoning associated with determining what the user's goals were, her activities, and particularly her *beliefs* about the ways things work in this application.

The third example deals with the possibility of having the computer act as an interviewer, to instigate Knowledge Acquisition procedures with the user as the source, to gain an understanding of a user domain of expertise (or requirement). One application might be to develop completely knowledge-based documentation for a system by interviewing the developers who played various roles in building it. The language difficulties of such a NLI application are manifold, including those of maintaining a coherent extended dialogue, somehow recognizing all of the various topics, understanding the user's qualifications, and following accepted "implicatures" for this type of interaction.

Whereas the first two examples deal with two levels of help for the user, and the third deals with helping the system acquire information, the fourth possibility concerns *cooperative* interaction between machine—and robot—to accomplish shared activities in the world. The most challenging problems here are not linguistic but rather those concerning beliefs: beliefs concerning each other's goals and immediate intentions, beliefs about the capabilities and available resources of the other, and beliefs about the present state of the world—and whether the other shares the same beliefs!! Instigating and coordinating belief statement and revision, particularly to maintain a shared world model, appear to be far more difficult than the linguistic problems of resolving referring expressions, communicating states, and issuing clear instructions.

It is a tribute to the remarkable progress in the natural language processing field—and to the memory/performance features of today's PCs and workstations—that suggestions for new NLI such as the above four can be so calmly and un-selfconsciously described; it's quite likely that they will be similarly received. With such progress it is likely that the key technical limitations to realizing these additional futuristic NLI won't be found in the computational or pure linguistic fields. Rather, they will probably come from the limitations of theory, method, and findings concerning the psychology of communication

and its intersection with pragmatics and semantics in various other fields. What an exciting challenge!

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Knowledge Representations Used By Computer Programmers[1]

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ABSTRACT

Composition and modification of computer program code are important skills requiring considerable cognitive effort. Psychologists have begun to study these skills both in order to understand complex cognitive phenomena and to contribute to the design of programming tools and aids. Research on the cognitive representations that programmers use is discussed. Many of the parallels between research and theory in natural language comprehension and programming language comprehension are highlighted. The procedural nature of program text and the fact that programmers are highly goal-directed makes for interesting contrasts with natural language. We describe our own work in this area which has led us to the opinion that code comprehension and modification are best understood in a problem-solving framework. The paper concludes with suggestions for programming tools that aid abstract reasoning about how to solve problems, not specific reasoning about how to write code.

Introduction

A computer program is a text, referred to as "code," written in a carefully formalized language, describing a set of instructions for a machine to follow. Often a program is accompanied by documentation, written in a less carefully formalized language, explaining to humans what the code "means." A program may also be accompanied by graphical information like flow charts or call structure diagrams that represent other aspects of its functionality.

We routinely accept the idea that a computer translates code into internal structures that are useful for guiding the machine through desired states. Considerable effort goes into the design of languages and physical architectures for the representation and realization of procedures that computers carry out. On the other hand, we have paid less attention to the representation of these same procedures by human beings. This despite that fact that the generation and modification, not to mention the underlying purposes, of computer programs still originate with humans.

The mandate for understanding the representational structures that humans use belongs to cognitive science, especially cognitive psychologists. Recently researchers in this field have turned their attention toward computer programming. There is much to be learned in this effort from prior research on natural language comprehension. In this study the knowledge utilized by programmers when they work with code is examined. In many places contrasts are made between the issues that arise in the study of natural language comprehension and computer program comprehension.

The first section discusses the representation of program statements and the processes involved in comprehending individual lines of code. This may be referred to as the "microstructure" level of representation. The next part covers the representation of aggregates of code. This is commonly referred to as the "macrostructure" level of representation. The third section treats knowledge outside of the programming language itself. This includes knowledge in the task domain and memories of other programs. The last section discusses the role of programmers' goals and strategies on representation and manipulation of code. The conclusion contains ideas for new directions in programming tools that support reasoning using the knowledge structures discussed throughout the paper.

Microstructure Representation

The basic unit of natural language is a sentence and the basic unit of a program is a line. In natural language a simple sentence expresses a single concept or relation. Complex sentences may contain several elementary concepts. Cognitive psychologists use *propositions* to represent simple concepts. A proposition is centered around a relational term that describes the association of several objects to each other. The proposition is derived from rules mapping symbols in the natural language to internal symbols in the representation language.

As an example, consider the sentence "John gave a sandwich to Bill." In natural languages verbs typically provide the relational term around which propositions are built, so a proposition for this sentence is derived from a general form like the following:

(GIVE, *actor, object, recipient*).

This form serves as a representational frame for all sentences of the same type. Thus, the example sentence would be represented as:

(GIVE, John, sandwich, Bill).

The advantage of propositional notation is that it allows sentences with different surface forms to be represented conceptually the same way. This is one theoretical way of handling the problem of synonymy. More importantly, however, this permits general rules to be written that utilize the conceptual information (memory searching rules, for example). If surface forms were maintained in the internal representations of concepts, then rules for reasoning and memory search processes would have to be specific to each possible representational variation.

Schank (1972) has claimed further that there are only a few canonical forms underlying the microstructure of a natural language. Thus, in Schank's *conceptual dependency* theory there is a primitive action (called "ATRANS") that represents any transfer of possession as the proposition:

(ATRANS, *actor, object, recipient*)

regardless of the verb used to express the concept. This allows all of the following sentences to be represented by the same logical form:

John gave a sandwich to Bill.
John gave Bill a sandwich.
Bill was given a sandwich by John.
John handed a sandwich to Bill.
Bill got a sandwich from John.

Evidence for propositional representations in natural language comes from several sources. One is confusion errors in recall for synonymous surface forms (Flores d'Arcais, 1974; Sachs, 1967). A subject who reads "Mary was given a rose by John" may mistakenly identify "John gave a rose to Mary" or "Mary got a rose from John" on a later recognition test, for example. In a study by Anderson (1974), subjects asked to judge whether a sentence meant the same thing as a previous sentence initially did so more quickly when the two sentences matched verbatim. After 2 minutes, however, a sentence with a different surface form but the same meaning was judged just as quickly as a verbatim match. Many researchers agree that information about the surface features of a sentence are encoded and persist for a limited time in short term memory but that only propositional forms are encoded in long term memory.

Other evidence for propositional representations in natural language comes from reading-time studies. In natural language reading times are predictable partly by the number of underlying propositions that are contained in a sentence. The sentence "The car lurched and chugged" contains two propositions, one for "The car lurched" and one for "The car chugged." Controlling for sentence length, Kintsch (1974) and Kintsch and Keenan (1973) have shown a linear relationship between the number of propositions in a sentence and the reading time for that sentence.

Is there a propositional microstructure for programming languages? There are two reasons that this is a difficult question to answer. First, by design, programming languages are economical and it is rare to find more than one way of expressing a basic programming action. We might expect that a propositional form exists for assignment, for example:

(ASSIGN, *variable-name, value*),

but we would be hard pressed to find more than one way of expressing this in any one language. In a sense, the highly constrained syntactic rules for a programming language constitute its microstructure.

A second reason that it is hard to specify the microstructure of a line of code is that the line represents a procedure, not just a static concept. Mayer (1987) argues that a line of code is represented conceptually as a set of "transactions" to be carried out by the machine on which it will run. The transaction steps are determined by the programmer's mental model of the machine architecture and rules. For example, a statement of the form

variable-name = *value,* (e.g., A = 0)

would be represented as the following sequence of transactions:

(1) Find the value in the expression (e.g., read 0).
(2) Store the value in temporary memory (e.g., store 0).
(3) Find the value currently in the memory location of *variable-name* (e.g., find the current value of A).
(4) Erase the value in that memory location.
(5) Store the value now in temporary memory in the memory location associated with *variable-name* (e.g., associate 0 with A).
(6) Move to the next line.
(7) Do what the next line says.

Mayer (1987) has performed a reading time experiment on very short (3-line) BASIC programs, and Dyck & Auernheimer (1989) have generalized the experiment to Pascal. In Mayer's study subjects were shown a few lines of BASIC and the reading times were measured for each line. The number of "transactions" that were implied by each statement was a significant predictor of reading time, accounting for 56% of the variance in their data.[2]

We recently completed a reading time study for a long (135 line) Pascal program and our findings pose several questions (Robertson & Davis, 1990). One thing that we noticed is that "reading," in the sense that we use the term for natural language, is not what programmers do when they look at lines of code. When allowed to search through the code in any manner they choose, programmers move as easily backward through the code as forward. They return to lines over and over. They spend too little time on some lines to even

process the elementary features of the text, and they spend so much time on other lines that they could have studied a whole procedure instead.

We ran two groups of subjects, showing each the 135 lines of the program. One group saw the lines in a scrambled order while the other saw them in the coherent order of a program. We wanted to contrast these two situations because we reasoned that the reading times for the scrambled code would be "microstructure only" reading times, while the reading times for the coherent code would reflect other comprehension processes.

We used a simple model for deriving the code microstructure. The model, like Kintsch's simple model for natural language, assumes that a proposition is built for each concept in the line. The program line:

```
mean:=sum/n
```

can be represented by two propositions, one assignment proposition:

(ASSIGN *variable-name, value*)

and one arithmetic operator proposition:

(DIVIDE, *variable-1, variable-2*).

In our example one proposition is embedded within the other as follows:

(ASSIGN (mean, (DIVIDE, sum, n))).

In order to construct this proposition in memory, elementary concepts must be constructed for each variable (mean, sum, and n) and each operator (ASSIGN and DIVIDE). Other items that appear in lines that might be relevant to propositions are command names (function calls, conditional statements, etc.) and delimiters (parentheses, semi-colons, etc.). From this simple model we quantified the number of steps required to construct each component of the proposition for each statement in the program. We used each component of the proposition as a separate predictor as follows:

Reading time = #variables + #command names + #operators + #delimiters[3]

We predicted the reading times for each subject separately and here report the means across subjects.

This simple equation accounted for an average of 54% of the variance in reading times across subjects who saw the scrambled lines, comparing favorably with the 56% that Mayer found using the more complex transaction analysis. However, the equation accounted for only 23% of the variance in reading times for the group which studied coherent code.[4] While the regression

equation is a significant predictor in both cases, it is clear that much more variance is left unaccounted for when real code is being read. A closer look at what programmers were doing helps to explain this.

When programmers study a program they do not read through it in order as they would a text. Rather they skip back and forth through the code and view lines multiple times. In our study, the average line was looked at 5.6 times with some lines being returned to as many as 13 times. While subjects who read the scrambled lines spent an average of 6 minutes and 20 seconds in the experiment, the subjects who studied the program spent an average of 50 minutes and 16 seconds. Remember that both groups looked at the same 135 lines of code.

Virtually every subject who studied the coherent program made repeated regressions in the code, re-reading sections. When we categorized encounters with a line of code according to which direction the subject was moving when he or she read it, we discovered a major source of variation in reading times. We divided line encounters into four major categories. If a subject moved to a line from the previous line and then moved on to the next line, this was a forward encounter. If a subject was moving backwards through the code, arriving at a line from the subsequent line and then moving on to the previous line, this was a backward encounter. If a subject arrived at a line from the previous line but then returned to the previous line again on the next move, this was a forward-to-backward switch. If a subject was moving backward and arrived at a line from the subsequent line and then returned to the subsequent line on the next move, this was a backward-to-forward switch. Table 1 shows the average number of moves observed in each category. Seventy-two percent of the moves were forward moves, like normal reading of prose, seventeen percent were backward moves, and about eleven percent were switches in direction. Sometimes subjects read a few lines of code, switched direction and backed up to an earlier line, switched directions again and then read through the code a second time. We called these sequences of movements "episodes" and further subdivided our reading times into "within episode" and "between episode" sequences.

Table 2 shows the mean reading time per syllable for lines of code in each

Table 1.—Mean number of moves per category and proportion of total moves in each category

	Movement Category				
	Forward	Backward	Forward-Backward Switch	Backward-Forward Switch	Total moves per subject
Mean	593.2	138.0	44.0	44.0	819.2
Proportion	.724	.168	.053	.053	1.0

Table 2.—Mean reading times per syllable (ms) for movement categories within and between episodes

Movement Type	Between Episodes	Within Episodes
Forward	408	—
Backward	141	146
Forward-Backward Switch	1581	1027
Backward-Forward Switch	569	410
First forward pass	—	387
Second forward pass	—	225

movement category and each episode category.[5] This subdivision of reading times revealed that very different processes were taking place in each movement category. In particular, the long times at switches suggest that considerable cognitive processing was taking place when switching occurred, especially forward-to-backward switching. Also, it is clear from the rapid reading rates in the backward category that a very elementary analysis was taking place during backward movements.

Table 3 shows the application of our simple microstructure equation to reading times in the different movement categories. The mean proportion of variance across subjects accounted for by the equation is shown for each category. Also shown are the numbers of subjects (out of five) for whom various components of the equation were significant ($p < .05$). That number is marked with an asterisk when the predictor was significant for a majority of the five subjects.

The proportion of variance accounted for by the equation was highest for the subjects who saw scrambled lines, and all of the components except delimiters were significant for the majority of subjects in this group. We take this as evidence that a straightforward translation of the lines of code into an underlying propositional form is taking place.

Table 3.—Proportion of variance accounted for (R^2) by the microstructure equation in both statement presentation conditions and different movement categories. Also shown are the number of subjects (out of 5) for whom each predictor was significant (V = variables, C = commands, O = operators, D = delimiters). Asterisks indicate that the predictor was significant for a majority of subjects. The double asterisk indicates a negative coefficient for that predictor.

		Predictor			
Type of Statement Presentation	R^2	V	C	O	D
Scrambled Lines	.54	5*	4*	3*	1
Coherent Program					
Movement Categories Between Episodes					
Forward	.17	5*	2	3*	3*
Backward	.22	3*	2	4**	0
Movement Categories Within Episodes					
First Forward Pass	.34	2	1	4*	1
Backward	.27	3*	0	1	1
Second Forward Pass	.22	1	2	3*	1

The proportions of variance accounted for by the equation when predicting reading times in the coherent program group were all less than the scrambled condition. Further, different components of the equation were significant in the coherent program condition, and these components varied widely across movement types. *Variables* and *operators* were significant for a majority of subjects in the non-episode reading times, suggesting that cognitive processes occurring during this activity were more like those in the scrambled condition, i.e., more like normal reading. Within episodes, however, *variables* were not as consistently important.

We view this as evidence that the cognitive processing taking place at each line varies considerably depending on the overall goal of the programmer at the time. Programmers' goals vary as evidence is gathered about how the program works. In a later section we will discuss our view that comprehension of programs is problem-solving behavior, not normal reading, and present further data on this point. First, however, we turn from a discussion of the representation of lines to the representation of chunks of code.

Macrostructure Representation

In natural language a paragraph or a story is more than the sum of its sentences. Propositions derived from sentences are connected to each other in a meaningful way, and inferences are generated during comprehension that provide a complex memory structure in which to embed microstructural elements.

Complex memory structures are built by the generation of local inferences to connect stated elements. For example we easily see that the following two sentences are related:

John was hungry.
John went to a diner.

We would say that the two concepts are associated in memory by a "Reason" relation since we know that John is going to the diner *because* he is hungry.

Macrostructure relations can also be represented propositionally. The following proposition serves as a frame into which other propositions can be embedded if *proposition-1* is a reason for *proposition-2:*

(REASON, *proposition-1, proposition-2*).

Thus the two sentences about John can be turned into propositions and embedded in the following instantiation of the REASON frame:

(REASON, (HAVE, John, hunger), (GO, John, diner)).

Several theories of natural language comprehension hold that representations of connected prose can be thought of as hierarchical structures consisting of related macrostructure elements at superordinate nodes with microstructure elements at the terminal nodes (Graesser, Robertson, Lovelace, & Swinehart, 1980; Kintsch, 1976; Kintsch & Keenan, 1973; vanDijk & Kintsch, 1983). Recall experiments have tended to support this hypothesis, showing for example that memory is better for superordinate information than for subordinate information (Graesser, *et al.*, 1980).

Complex propositions at the macrostructure level capture inferences about the relations among stated propositions. The source of such inferences has been of considerable interest to researchers in natural language comprehension. *Scripts, plans,* and *goals* (Schank & Abelson, 1977; Seifert, Robertson, & Black, 1985; Warren, Nicholas, & Trabasso, 1979) are considered to be common sources of pragmatic inferences.[6]

A *script* is a knowledge structure that contains a sequence of the actions that constitute a common activity. People acquire many scripts and then use this knowledge to guide their actions and comprehension of actions when they are in script-like situations.

Bower, Black, & Turner (1979) asked subjects to describe what typically happens when the subjects performed several different activities like going to a restaurant or going to the doctor. For each of these activities there was a core set of actions that virtually every subject mentioned. Subsequent recall and recognition experiments showed that these core activities were present in subjects' memory representations of script-based stories even when they had been left out of the stories. A reading-tme study, also by Bower, *et al.*, showed increased reading time for script actions when a prior action was missing. This was taken as evidence that inferences about script-based actions are generated when necessary during comprehension. These inferences connect the microstructure of a story in the final cognitive representation.

Reading-time data from Seifert, Robertson, & Black (1985) provided evidence that inferences about goals and plans are also routinely made during comprehension. Recognition data from the same study showed that these inferences become part of the memory representation.

In programs there are also links between statements, and in fact the local inferences about how statements are connected are often more reliable in programming languages than in natural languages. For example, a BEGIN statement in Pascal will always be accompanied by an END statement, a FOR statement in Basic will always be accompanied by a NEXT statement, and so on. Compilers make use of these mandatory contingencies to recognize simple

syntax errors. Also, some program editors make use of these rules by providing the programmer with the complementary statements. The boundaries of code searching episodes found by Robertson & Davis (1990) very often consisted of these procedurally related statement pairs.

What is interesting about connections among lines of code is that they achieve code functions. The FOR-NEXT construction in Basic or the DO-UNTIL construction in FORTRAN achieve the iteration function, and this function must be accompanied by loop control processes. All programming languages contain constructs for iteration and all must have a way of indicating the scope of the iteration and controlling the number of iterations. This general knowledge about how programs do things has come to be called "plan" knowledge (Ehrlich & Soloway, 1984; Rist, 1986; Robertson & Yu, 1990). Several researchers suggest that good programmers acquire a repertoire of plans that they can access to comprehend and design code (Adelson, 1981; Guindon, 1990).

Rist (1989) characterizes programming plan knowledge by identifying the *focus calculation, goal output,* and *extension initialization* of common plans. For example, the *running total* plan has an accumulation operation as its focus calculation

(e.g., count: = count + 1, in Pascal)

the value of the accumulating variable as its goal output (e.g., the value of *count*), and an assignment operation as its extension initialization (e.g., count: = 0, in Pascal). Rist (1989) presents verbal protocol data in support of the view that programmers use plans in the design of code.

In a recent study (Robertson & Yu, 1990) we attempted to show that programming plans were abstract knowledge structures that were not specific to a language. We asked programmers to read several programs, divide them into meaningful "chunks," and provide a verbal label for the chunks. Then we asked them to sort the programs into groups—placing those that seemed to work the same way into the same group. We had written the programs to do many different things, from simulating a calculator to running a psychology experiment, but we used three distinct program schemas—or "plans." One plan, for example, was to show a menu, wait for a selection, act on the selection, and display a result.

Our subjects chunked the programs which were in the same plan groups in the same way, provided similar labels within those groups, and sorted the programs into groups according to the plans. Interestingly, the experiment was run using both FORTRAN and Pascal code, and the results were the

same regardless of the programming language. We interpreted this as evidence that plan knowledge for programming is more abstract than knowledge about the programming language (Adelson, 1981).

A second group of subjects was given the verbal labels that the first group of subjects had provided (both FORTRAN and Pascal labels mixed together) and was asked to sort them into similar categories. A clustering analysis of their sorting data is shown in Figure 1. Programs that were in the same plan group are indicated by groupings within parentheses just below the Figure's abscissa (there were three plan groups). "F" programs represent FORTRAN programs while "P" programs represent Pascal programs. It is evident that the subjects perceived the plan groupings across both tasks and languages. Only two programs, F2 and P8, out of eighteen were out of place.

To summarize, program representations include the relations between statements. These relations encode procedural associations between lines of code and are generated by inferences based on knowledge of common programming

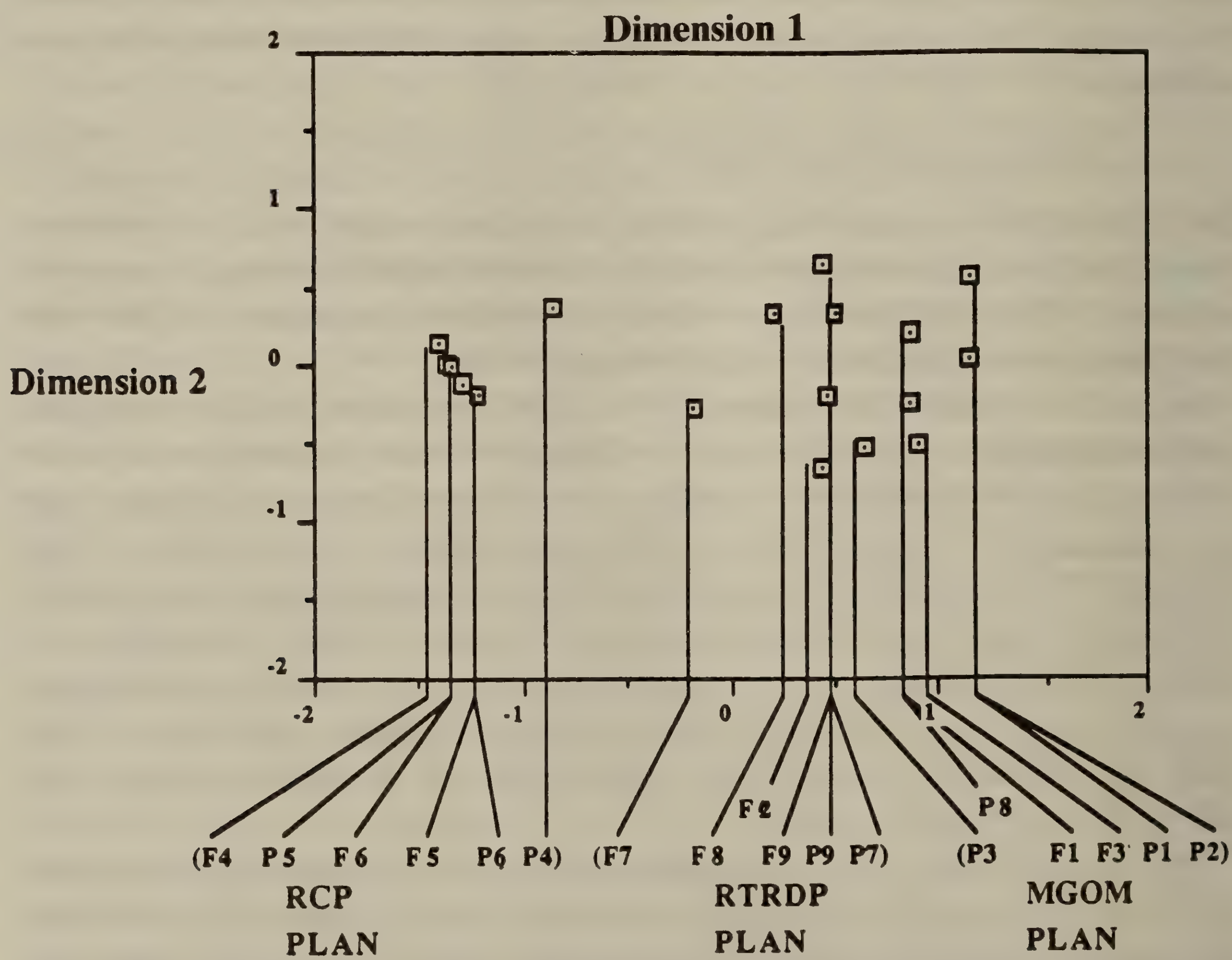

Fig. 1. Clustering analysis of sorting data from the verbal labels given to Pascal and FORTRAN programs in three plan groups (after Robertson & Yu, 1990).

constructs like plans. These procedural constructs are more abstract than knowledge about a specific programming language and develop as programming expertise increases.

Task and Function Representations

Another aspect of representation of both natural and programming languages concerns information that is entirely distinct from the text. For natural language this includes world knowledge, or context, which can have a significant influence on the perceived meaning of sentences. For programming languages, this includes the task domain or the problem that the program is designed to solve.

Several lines of research illustrate this point for natural language comprehension. These include research on "advance organizers" (Barnes & Clawson, 1975; Mayer, 1976, 1979b), the role of titles or context statements (Bransford & Johnson, 1973), and comprehension of conventional language usages like indirect requests and idioms (Clark, 1979; Gibbs, 1984, 1986; Gibbs & Mueller, 1990).

An advance organizer is a text item, like a title, outline, or diagram, that is presented to a comprehender before a text is read. Advance organizers have considerable influence on the interpretation that readers have of subsequent text. In an extreme example, Bransford and Johnson (1973) constructed stories that were incomprehensible to subjects when advance organizers were not presented, but which seemed mundane and easy to understand when they followed a clarifying picture or title. In other studies, the use of outlines, summaries, questions or other extraneous material as accompaniments to text enhanced memory for important text information (Anderson, 1980; Anderson & Biddle, 1975) and increased problem-solving ability (Bransford & Franks, 1976).

It is possible that very basic comprehension mechanisms may be affected by prior information. Psychologists have long been interested in the processes underlying indirect language usage (e.g., "Do you have a watch?" as a request for the time of day). Reading-time studies for indirect requests have shown that they take longer to understand than direct requests and a two-step comprehension model has been proposed to account for this result (Clark, 1979). In this model the literal meaning of a sentence is first determined. If the literal meaning does not make sense or violates what Grice (1975) called a conversational postulate, then the comprehender attempts to determine a possible non-literal meaning.

Research by Gibbs (1984, 1986), however, has shown that reading-time increases for indirect language usages disappear when the context suggests a conventional, but non-literal interpretation. For example, if the sentence "Do you have a watch?" is preceded by a sentence like "Mary didn't know what time it was so she stopped a friend," it is read quickly, interpreted non-literally (i.e., as a request for the time), and no apparent ambiguity is noticed. Thus it appears that the basic sentence understanding mechanism can be affected by prior context.

Advance organizers have an effect on comprehension because they allow comprehenders to activate relevant knowledge structures that can then be used to represent and elaborate the text information most effectively. This occurs because top-down processes play an important role in comprehension. There is every reason to believe that this is true of program comprehension as well. The problem is to determine which types of advance organizers will be most useful.

Mayer (1979a, 1981) has studied the role of advance organizers in the acquisition of programming knowledge. Again, the procedural nature of code changes the form of what makes an effective advanced organizer. Mayer reasoned that subjects would learn a programming language more quickly if they had a "mental model" of the device on which the code would run. Subjects who studied such a model (a metaphorical description of a computer system as a combination blackboard and filing system) were able to pick up the Basic programming language more quickly and use it with fewer errors.

Fitter & Green (1979) have explored the types of diagrams and illustrative materials that are useful to programmers. They suggest that auxiliary material should help programmers focus on the information that is relevant to their needs and, most interestingly, that the perceptual code of the material should match the representational code that will be used by the programmer to solve problems.

Several researchers have focussed on the form of the information given to programmers (Brooke & Duncan, 1980; Cunniff & Taylor, 1987; Kammann, 1975; Ramsey, Atwood, & VanDoren, 1983; Sheppard, Kruesi, & Bailey, 1982; Shneiderman, 1982; Shneiderman, Mayer, McKay, & Heller, 1977), with the most common form being some type of graphical representation like a flowchart. In general, this material is helpful to programmers when they use it, but a recent study in my laboratory (Koenemann, 1990) suggests that programmers spend as little time as possible with material extraneous to the code itself.

A twist on the notion of using graphical representations as aids to code comprehension is to represent the program itself graphically instead of tex-

tually. Cunniff & Taylor (1987) report that programs written in a graphical programming language called FPL are comprehended more quickly and accurately than programs written in Pascal. The significance of work of this nature will increase as object-oriented programming becomes more common and as programmers begin to appear who have never had experience with text-based programming languages.

In an interesting verbal protocol study of program comprehension, Pennington (1987a) observed that programmers who attained a high level of comprehension were concerned both with the program structures and with the application domain and that they mixed study of both aspects of the program. In an explicit attempt to relate code comprehension to the prose comprehension studies of Kintsch (1986) and VanDijk & Kintsch (1983), Pennington suggested that programmers build two distinct models. One, the *program model,* consists of code microstructure and macrostructure and represents the procedural detail of the program. A second, the *situation model,* consists of information about the real-world objects that the program manipulates, the real-world consequences of program actions, and the functional properties of the program in the task domain. The two models must be "cross-referenced" so that reasoning can occur easily about the correspondence of parts of both models. Later Pennington (1987b) elaborated her model and suggested that programmers first build the procedural representation from their knowledge of programming conventions. They then use this representation to help them understand the functional characteristics of the code and its relation to the task domain.

To summarize, programmers represent more than the microstructure and program-based macrostructure of code. Their conceptual representations of programs also include knowledge about the task domain and other functional characteristics of the code. A detailed model of the processes that generate this knowledge is lacking, although it is clear that presenting programmers with information that helps them conceptualize these aspects of code functionality is worthwhile.

Goals of the Programmer

A final issue that is important in understanding code comprehension is the nature of the programmer's goals. A programmer may be inspecting code for bugs, reading code to get an idea, searching code in order to make a modification, and so on. Each of these goals leads to a different strategy for code comprehension. Again, research in text comprehension has shown that sub-

jects make different kinds of inferences, and hence end up with a different representation of a text, when their reading goals differ (Frederiksen, 1975).

Some researchers (Jeffries, 1982; Nanja & Cook, 1987) have suggested that programmers who have a specific goal in mind, modification for example, read the text of the code for comprehension first. Under this view a more-or-less complete representation of the program is built before problem-solving on the programming task begins. Others, however, have noticed that programmers read code strategically when they have specific goals in mind and this has led to the view that they may build only partial representations as necessary for achieving their goals.

In a recent study Koenemann (1990) observed the behavior of programmers as they sought to make several modifications in a very long Pascal program. He found that programmers only looked at between 12% and 43% of the lines of code when their task was to modify the code. Further, the particular lines studied varied considerably within the same program depending on the modification task. He proposed that programmers follow an *opportunistic relevance strategy,* trying to determine which parts of the code they need to understand in order to make their modification and then only studying those parts. Littman, Pinto, Letovsky, & Soloway, (1986) made a similar observation, noting that good programmers pursue what they called an *as-needed* strategy in comprehension. Interestingly, novice programmers in that study utilized a more comprehensive strategy than experienced programmers did to understand the code.

Several other researchers have noted the strategic nature of code inspection and comprehension when the programmers have clear goals (Letovsky, Pinto, Lampert, & Soloway, 1987; Littman, Pinto, Letovsky, & Soloway, 1986; Myers, 1978; Weiser, 1982). This has led to a general consensus that we must begin to understand the problem-solving goals of programmers in order to characterize the processes that guide their actions (Gray & Anderson, 1987; Guindon, 1990; Letovsky, 1986).

As the result of several of our own studies of programming knowledge and programmer behavior we have begun to view program comprehension, and especially modification, from a problem-solving perspective. This perspective stresses the importance of programmers' goals, prior knowledge, and strategic decision-making processes. Programmers seldom, if ever, just "read for comprehension."

In order to help us understand programmers' strategies more clearly, we asked a group of programmers to repeat the experiment reported above (Robertson & Davis, 1990) in which a 135-line Pascal program was inspected. We again collected data on where subjects looked in the code and how they

searched, but we asked them also to stop periodically (at times that they determined) and explain what they were doing.

We categorized the programmers' movements according to the scheme described in Robertson & Davis (1990) and Table 4 shows the proportion of movements in each category (a comparison with Table 1 shows that the distribution of movement types was similar in this study to the earlier study). What is of interest is the distribution of comments across these movement categories.

The five programmers in this study provided us with 182 comments on their activities. By assuming that the comments should be evenly distributed across the movement types by chance, we determined the expected frequencies of comments in each of the movement categories based on the proportion of movements in each category (from Table 4). Table 5 shows the expected frequencies and the observed frequencies of comments that occurred in each movement category. There were many more comments than expected (by chance) that occurred in conjunction with switches in direction. Together with the observation that line reading times tend to be very high at these positions (Table 2), a consistent explanation is that considerable problem-solving activity is associated with changes in direction in the search sequences.

We were able to categorize the programmers' verbal comments into six groups: Analyze, Assume, Question, Answer, Function, and Strategy. An *analyze* comment was one in which the programmer offered an explanation of a code segment. An *assume* comment was one in which the programmer offered a prediction about what was coming up. A *question* was a query about the code. An *answer* was a statement that could be clearly linked to an earlier question. A *function* comment was a statement about what the code did functionally. A *strategy* comment was a statement about what the programmer planned to do next, usually where they wanted to go in the program or what kind of information they wanted to find out.

Table 6 shows the proportion of comments of each type that occurred in the movement categories defined for this experiment. The two most frequent

Table 4.—Mean number of moves per category and proportion of total moves in each category for subjects who made comments

	Movement Category				
	Forward	Backward	Forward-Backward Switch	Backward-Forward Switch	Total moves per subject
Mean	774.8	307.6	78.0	78.0	1238.4
Proportion	.626	.248	.063	.063	1.0

Table 5.—Expected versus observed frequencies of comments in each movement category. Expected frequencies reflect a chance distribution. A chi-square test suggests that comments were not distributed among the movement categories by chance, χ^2 (3) = 138.28, $p < .001$.

	Movement Type			
	Forward	Backward	Forward-Backward Switch	Backward-Forward Switch
Expected Frequency	114.7	45.5	10.9	10.9
Observed Frequency	102.0	13.0	23.0	44.0

comment types in each movement category are marked by asterisks. Note that the functionality of the code was the topic of most of the programmers' comments. This was true for each type of movement except backward movements. Apparently subjects do not discover as much about code functionality when they are moving backwards. Inspection of the backward movement category shows that questions and strategy are the primary concerns when programmers regress through the code. Strategy comments are also prevalent when programmers switched from the forward to the backward direction.

The unequal distribution of comment types across movement categories shows that programmers have qualitatively different things in mind as they move around in code. We are working now on a model of programmers' goals and comprehension strategies that would account for the differences in reading times and comment types that co-occur with changes in reading direction.

Comments on Programming Tools

Designers of programming tools who are interested in supporting the cognitive processes and problem-solving strategies of programmers will have several issues to take into account. First, the actual lines of code are the least important aspects of a program from the point of view of long-term memory

Table 6.—Proportions of comments of each type within the movement categories. The two most frequent comment types within each category are marked by asterisks.

	Movement Type			
Comment Category	Forward	Backward	Forward-Backward Switch	Backward-Forward Switch
Analyze	.078	.053	0	.074
Assume	.219*	.158	.167	.220*
Question	.078	.263*	.125	.118
Answer	.094	.105	.083	.118
Function	.422*	.158	.250*	.368*
Strategy	.109	.263*	.375*	.103
	1.0	1.0	1.0	1.0

and problem solving. Information about the surface details of program statements is probably lost soon after a statement is read. Only the meaning of a statement, which corresponds in programming to its functional significance, is retained. Even at the statement-level meaning representation is only useful in recognizing larger functional units like loops or conditional clauses.

The fleeting significance of statement-level representations suggests that improvements to programming interfaces which enhance readability or otherwise aid in the recognition of lines of code will have limited influence. Rather, enhancements that improve the recognition of meaningful code segments would be more useful. Designers of programming tools should focus on presenting information about the functionality of each line to programmers since this seems to be their final goal anyway when they read a line of code.

Second, pragmatic inference generation is an important part of program comprehension. Inferences provide the links between program statements which eventually form the macrostructure representation of the code. Interestingly these types of connections are often not explicitly made in the code (they may be present in comments, but commenting is an unreliable art form). Programming tools that explicitly mark high-level connections between code segments would be useful. One possibility is a hypertext environment in which the hierarchical structure of code elements is represented and can be used to maneuver through the program.

If good programmers learn a set of plans that they use over and over, and if these plans have typical instantiations within a given language, then it should be possible to construct a programming tool that generates the code for given plans directly. For example, when a programmer wishes to create a loop that will keep a running total, he or she might instruct the programming tool to create the code for a running total in Pascal with the accumulation variable named *var1*. Once created, the tool should keep track of the various pieces of code that belong to the plan (e.g., an initialization of *var1,* the accumulation statement, the loop control statements, the variable that holds the final output value, etc.) so that changes in one part of the plan are propagated throughout the plan—even if it is widely distributed spatially in the program.

A third issue relevant to programming tool design is related to the multiple representations utilized by programmers. We saw that programmers not only represent the procedural components of code, but also the functional relations of code segments to each other based on the real-world semantics of the problem that the program handles. Tools should help programmers encode (in the design phase) and understand (in modification or comprehension tasks) the semantics of the domain and the constraints it places on the code itself.

A useful, though difficult, tool would provide programmers with a "semantic

compiler" that works the way syntactic compilers now operate. A semantic compiler would recognize (or at least represent) functional relations and trap violations of the semantics of the code. For example, such a tool might recognize errors in the ordering of function calls if the effects of one function enable the operation of another in the real world application (e.g., in an elevator control program a function that initiates the movement of one of the elevators should be called after a function that assesses all waiting requests for the elevator). A modification to the code that resulted in an inadvertent violation of this semantic constraint should be trapped. Such a tool might go further in suggesting how to structure a program to help avoid inadvertent semantic errors (e.g., the tool might suggest to the programmer of the elevator program that placing the call to the request assessment module within the movement module would minimize the chance of later violating the constraint on their ordering).

Finally the issue of programmers' goals might influence the design of tools. A debugging or modification tool should be different from a design tool, and these in turn should be different from a maintenance tool. A programmers' goal first affects the manner in which he or she wishes to search through the code. In modification and debugging, programmers want to minimize the amount of code that they look at, focussing only on those parts that are relevant to the required changes. Their search strategies emphasize finding functionally related components of the code and checking blocks of code for syntactic consistency. Designers and maintainers might need to search code according to the requirements of the task domain. Their search strategies might involve finding all function calls that affect a certain action in the real world—and a tool should help them do this.

In addition to search strategies, different goals affect the problem-solving processes of, and hence the information required by, programmers. A programmer making a fix in a function wishes to reason locally, within the scope of the function and perhaps those functions called by it. On the other hand, a programmer or a designer making a major change in the functionality of a whole program wishes to reason more globally. The information that these two individuals require and the types of decisions they will make are quite different. Designers of programming tools should have these considerations in mind.

Conclusion

Research on the cognitive processes and knowledge structures underlying program comprehension and modification have been discussed. Four major issues were identified as important in understanding comprehension: micro-

structure representation, macrostructure representation, task and domain knowledge, and programmers' goals. While there are many similarities between theories in natural language comprehension and program comprehension, the procedural nature of programs and their role in controlling real-world processes makes program comprehension an especially complicated matter.

In theorizing about the processes involved in program comprehension it may be most fruitful to think in terms of problem solving. This view increases the importance of programmers' goals and makes comprehension a less homogeneous phenomenon across tasks and programmers. It makes search strategy and selective representation central issues as well. These changes in focus in understanding program comprehension have implications for the design of programming tools.

Programming tools should support high-level reasoning in several different domains. The constraints on program structure due to the semantics of abstract programming constructs and a program's functionality in the task domain are the primary concerns of programmers. These relations are not systematically present in the code itself or even in the supporting documents. Tools that make these constraints easier to understand and that support reasoning and modification at these levels of representation will be the most useful. While the technology is probably there to implement such programming aids, our understanding of the structure of these representations and how they are used in problem solving limits our ability to take advantage of it.

FOOTNOTES

[1]In this paper I discuss work conducted in my laboratory by Erle Davis, Doug Fitz-Randolf, Jurgen Koenemann, Kyoko Okabe, and Chiung Chen Yu. The work was supported by the Office of Naval Research under contract number N00014-86-K-0876.

[2]Mayer does not report the proportion of variance for this test. Rather he reports a correlation of .75 between number of transactions and reading time. By squaring this coefficient we derive the proportion of variance for which the predictor accounted.

[3]The equation is actually predicting log(reading time). Log transformations are commonly performed on skewed data, especially time data which has a minimum of zero but no maximum. The transformation creates a more normal distribution and does not affect ordinal relations. Interval relations are affected only in the extremes.

[4]This omnibus figure glosses many details. Below we discuss a breakdown of this analysis.

[5]Dividing by the number of syllables controls for line length and makes the reading times directly comparable.

[6]Pragmatic inferences are distinguished from logical inferences in that they are not necessarily true.

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The Human Factors of Voice Interfaces

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ABSTRACT

Speech recognition and synthesis devices are examined for their present-day capability to function as effective interfaces to computer-based systems, and their limitations are identified. Some guidelines on the utility of those devices are offered but the practitioner is cautioned that the adoption of those systems will be highly dependent on the specific user-population, task, and context.

The technology for recognizing speech, synthesizing speech from text, verifying the identity of speakers, and digitally storing and manipulating human speech has seen tremendous advances over the past few decades. In order to help design efficient human-machine systems, the human factors specialist must be aware of not only the uses of such technologies and the growing literature on how to use these technologies most effectively, but also understand something of the underlying technologies. I will begin by describing the state-of-the-art in automatic speech recognition. I will also say something about the underlying approaches and where the technology is likely to go. I will then discuss the kinds of situations for which speech recognition as an input medium to a machine is particularly appropriate. Then, some tentative guidelines will be presented based on the growing experimental literature in this field. As always however, it will be necessary to test the details of any particular system for the users, task, context, and specific system that is of interest to the particular human factors investigator.

Another technology which has seen substantial progress is the area of text-to-speech-conversion, otherwise known as speech synthesis. This latter term however, is also sometimes used to refer to systems that digitize human voice and play it back later (speech encoding and decoding). The quality of digitally

encoding, storing, and later reconstructing human speech is only limited by the money that one is willing to spend for storage. In contrast, unlimited text to speech conversion, i.e., speech synthesis, is not yet as intelligible as human speech and not nearly so aesthetically pleasing. I will describe in more detail the state-of-the-art in speech synthesis and briefly outline some of the approaches. This will be followed by a discussion of the factors that would lead one to consider using speech synthesis in an application. Of necessity, this discussion will also touch upon speech encoding and decoding as an alternative. I will present some guidelines concerning the use of speech synthesis.

Finally, I will briefly describe some additional voice technologies that can be used today or in the near future. These include speaker verification, word spotting, language identification, affect detection, and speech detection.

Automatic Speech Recognition

The state-of-the-art

The state-of-the-art in automatic speech recognition, as in many other new technologies, is a rapidly moving target. As we will see, both the overly optimistic view that speech recognition is a panacea and already exists in such a form as to provide an automatic unlimited speech conversion system, and the pessimistic view that speech recognition is still far off in the future, are equally fallacious. The truth of the matter is that for certain applications (spelled out in more detail below), speech recognition already provides a reasonable interface for human input. In order to understand the current state-of-the-art, it will be necessary to review some of the dimensions on which speech recognition systems vary.

One important dimension is the degree of independence of the system to the various accents, speaking styles, and vocal tract shapes of individual speakers. Systems which are geared to and must be trained on specific individual speakers are referred to as "speaker-dependent" systems. At the other extreme are systems which are called "speaker-independent" systems. Other things being equal, speaker-independent systems are typically much more limited in their capabilities than speaker-dependent systems. One reason for this may be that, although it seems clear that human listeners quickly adapt to individual speakers, automatic speech recognition devices have not typically made use of this facility.

Another important characteristic to understand about speech recognition devices is the acoustic environment in which they operate. To take one common and important example, the telephone network typically band-passes

speech between three hundred Hertz and thirty three hundred Hertz. In addition, some noise and other types of distortion may be introduced. This makes speech recognition more difficult. Similarly, a speech recognition system that must operate in the presence of large amounts of environmental noise, particularly if this noise includes human speech, will be at a disadvantage relative to a speech recognition device operating in a noise free environment. Speech recognition has also been investigated for use in airplane cockpits for fighter pilots. In such an environment, not only is noise a problem, but also the G-forces to which the pilot is subjected.

A third dimension for consideration is the degree to which the user's behavior is constrained to be unnatural in a given situation. One important way to constrain user behavior is to limit the available vocabulary. To take one extreme example, if a speech recognition system need only discriminate between the words "no" and "I here answer in the affirmative," then it will probably do quite well. As vocabulary size increases, the chances of two words being similar enough acoustically to be confused by the recognizer increases. Not only do most speech recognition systems enforce limitations of vocabulary, but often on the manner these vocabulary items are put together. For example, the system may require discrete utterances; that is, the user must pause between each word. In a continuous speech recognition system, the user speaks in a more normal, continuous fashion. For the recognizer to deal with this continuous speech, it must not only recognize words but segment the continuous stream of speech into the individual words as well. In addition, the continuous speech recognition problem is made more difficult because in continuous speech the co-articulation effects at the word boundaries can be quite strong.

A fourth set of considerations has to do with the time to process, the cost of the device, and other operating constraints. If a system costs a million dollars, it will probably not find its way into every telephone set, no matter how good the performance. Whether or not the system needs to recognize speech in real time will depend upon the application.

The point for the human factors professional in understanding these dimensions is that speech recognition accuracy, in and of itself, has no meaning. Recognizers can only be compared when it is clearly understood what the conditions of testing were and what the conditions of actual use will be. For example, if one uses one's colleagues and has them read telephone numbers over the phone, the accuracy performance results will probably be quite different than if one requests naive users to speak telephone numbers that they have just dialed.

As noted above, specific accuracy figures can be very misleading and speech

recognition devices must be tested under conditions of actual use. For this reason, I intend to give the reader some feel of what is generally possible. The reader, in turn, must keep in mind that actual results will depend upon the particular vocabulary items chosen, the range of speakers who will use the system, the acoustic condition of the system that will be used, and a variety of other factors. Broadly speaking however, we can say that speech recognition devices exist today which will operate in a quiet office environment and understand a large vocabulary (on the order of a few thousand words) provided the system is trained on an individual speaker and provided the speaker inserts pauses between each word. Whether or not such a device constitutes an acceptable substitute for human transcription must be looked at in the context of a specific application.

Smaller vocabulary speaker-trained devices have been profitably employed in industry for sorting and inspecting. In such cases, there is typically some background noise. The systems typically allow more efficient input of data than do other alternatives. With regards to over-the-telephone speech, both speaker-independent and speaker-dependent systems suffer somewhat. Speaker-dependent systems exist which will allow up to twenty to fifty words discretely uttered, to be recognized at any one point. The total vocabulary can be larger provided that there is a clear a priori way of knowing at which point in the dialogue various words can be uttered. Speaker independent systems are limited at this point to the digits, yes, no, and perhaps a few control words. The state-of-the-art demonstrates that systems can recognize a fair proportion of speakers saying continuous digits over the phone.

Applications of Speech Recognition

Speech recognition technology can serve as an alternative input device. While the advisability of using speech must be examined on an individual basis, and if it seems like a reasonable input modality, tested under conditions of use, there are some general guidelines for which applications are likely to prove amenable to automatic speech recognition.

There are people for whom keyboard entry is not an option; for example, children learn to talk several years before they learn to read and type. In many parts of the world, there are also large populations of adults who can speak in a particular native language quite fluently but who are unable to read or type. Aside from this, speech recognition is particularly suitable when the person's eyes/hands are otherwise occupied and therefore keyboard entry becomes cumbersome and time consuming. It is largely for this reason that speech recognition is used in several industrial applications involving inspec-

tion and sorting tasks. Because speaker dependent systems typically have higher accuracy rates and/or larger vocabularies than speaker independent systems, speech recognition is typically feasible over a wider range of applications where there are dedicated users involved who will spend the time to train the speech recognition device on their particular speech pattern.

About 40% to 50% of the phones in the United States are still of the rotary type. The use of automatic speech recognition (ASR) over the telephone allows many telephone-related services to be used by all subscribers and not just those possessing touch-tone service. One may also argue that even for touch-tone subscribers, speech is a more natural form of input. Factors mitigating against the use of automatic speech include a heavy penalty for errors. Almost no current speech recognition system is 100% or even 99% accurate. Therefore unless there are additional ways of insuring safety, speech recognition is probably not the input medium of choice where a single error can have extremely costly results. It is problematic to use with one time customers since it may be difficult to arrange the situation so they will naturally contain their speech in the ways that are currently necessary for speaker independent systems.

Speech recognition systems can thought of, not only as alternatives to manual input, but as supplements. For example, a combination speech recognition and handwriting recognition system would be much more accurate than either system by itself. One can also imagine a very natural text-editing system in which the operands or areas to be operated on were specified manually (for example by mouse or trackball) and the operators specified by discrete voice commands.

For speaker-independent systems, there are typically some proportion of speakers for whom the system works quite well within the constraints of vocabulary rate etc., and some speakers for whom the system does not work very well at all. Because of this it will be necessary in the case of speaker independent applications to have a non-speech backup.

The most important thing to say about guidelines is that they should be used as tools, not rules. We do not know enough to make rules. In addition, the technology changes. Finally, systems must ultimately be tested for real use by real users in a real context doing real tasks. While readers should find the references at the end of this paper useful, I have refrained from the practice of relating guidelines to references. I believe correlating specific guidelines to specific references grossly overstates the empirical basis for today's human factors guidelines. The guidelines are better thought of as personal best-guesses based on intuition, experience, and a reading of experiments that are sure to be done under different conditions than the application of interest. Table 1 shows architectural guidelines. Table 2 lists guidelines for recognition.

Table 1.—Architectural Guidelines

- Consider "Wizard-of-Oz" prototyping for capabilities that are difficult to implement and the team disagrees on value.
- Use high level prototyping languages initially.
- Never let a bad feature slip by now to be fixed later. Insist on quality throughout.
- Consider writing user manuals first—to drive architecture.
- Circulate to all development team members a description of the product from the end-user's perspective.
- Define the end-user(s), task(s), context(s).
- Provide a "Home Base".
- Provide "Undo" capability.
- Use table-driven interface.
- Put all messages in one place in the code.
- Use variable length fields for messages, prompts, etc.

Guidelines For Using Speech Recognition

Prior to describing specific guidelines for the application of speech recognition devices, it may be useful to point out several general principles. While one of the advantages of speech recognition is touted to be its naturalness, the fact of the matter is, current systems will require some deviations on the part of the user from their natural speech habits. Some care must be given therefore to selecting a limited vocabulary which contains items which are acoustically dissimilar enough to be recognized and yet which also contains enough items to appropriately cover the domain of interest. It should also be noted that users may well attribute too much intelligence and human-like capability to a system that uses speech recognition as an input. For example, they may expect the system to understand that synonyms refer to the same item. Commonly, when the speech recognition system does not understand the user's first try on a trained word, the user's natural reaction is to speak the word more loudly and distinctly than before. This of course, decreases the chances for speech recognition systems to recognize the word spoken.

Text to Speech Synthesis

The state-of-the-art

Speech synthesis systems convert text in ASCII or EBCDIC into spoken speech. The process of converting written or printed text into internal com-

Table 2.—Recognition Guidelines

- Use ASR where errors are not catastrophic.
- Provide an alternative (back-up) to ASR, especially in speaker independent systems.
- Use ASR when eyes/hands are busy.
- Have users participate in vocabulary design.
- Make sure users are immediately signalled that they are using ASR.
- Make the "training" situation like the "use" situation.
- Test the ASR in its real environment with the real users.

puter codes is a separate process that will not be discussed. In converting text (inside the computer) into speech, several separate sets of problems must be addressed. First, special handling may be required for the appropriate reading of abbreviations, numbers, and special symbols and signs. This task is not as trivial as it may sound. There are many fairly arbitrary conventions that must be followed. For example, the capital letters without periods "IBM" are usually pronounced as separate letters: "I-B-M" whereas the capital letters "RBOC" are generally pronounced "Are-Bok". "Dr." can be pronounced "Doctor" or "Drive" depending upon the context. When the numbers 1492 appear, they are pronounced "Fourteen-ninety-two" in the context of a date. In the context of net profit however, it may be pronounced "One thousand four hundred and ninety-two." In pronouncing a transcription of someone's notes, an ampersand should be read as "and", while in context of a computer language the ampersand should probably be pronounced "ampersand." Current speech synthesis systems do fairly well in such matters. It should be clear however, that doing perfectly (i.e., as a human being would do it) is equivalent to having a general purpose natural language understanding system. Instead, current synthesis systems rely on fairly simple-minded statistical context rules for making such decisions.

A second challenge facing speech synthesis systems is the translation from a string of orthographic characters to units of pronunciation. The so-called letter-to-sound rules are particularly irregular for English. This is illustrated by George Bernard Shaw's famous example of how one might pronounce "GHOTI";/ namely, "fish." In this example, "GH" is pronounced as it is in the word "rough." The "O" is pronounced as in the word "women". Finally, "TI" is pronounced as in the word "nation." Generally, common words in English are likely to be more irregular. For this reason, most speech synthesis systems have an exception table. If a word is found in the exception table, an associated pronunciation is used. If not, letter-to-sound rules are used for pronunciation. The problem is particularly difficult in dealing with proper names. Commercially available systems may only pronounce 50% of proper names correctly. Research systems do substantially better.

Aside from the difficulties and vagaries of English pronunciation, there is the further problem that many words (over two hundred) in English are pronounced differently depending upon the context. These non-homophonic homomorphs are pronounced differently depending on the part of speech or which of two words is meant. For example, "does" as an auxiliary verb is pronounced "duz" while as the plural noun for female deer is pronounced "doze." In other cases, even two nouns can be pronounced differently. For instance "bow" is pronounced to rhyme with "bough" when it is the front of

a boat but to rhyme with "beaux" when it is a ribbon configuration. Again, current synthesizers rely on fairly simple-minded statistical context and sentence-position rules to make a guess about which pronunciation in such cases is likely to be correct. However, in the absence of an adequate parse, such systems will always be prone to error.

Given that a sequence of phonemes for individual words is correctly decided upon, the synthesizer must then do the work of actually pronouncing this string of phonemes. There are several approaches to this task. Two main variables are the choice of the unit of pronunciation and the manner in which these units are conjoined. The units of speech are either segments of actual human speech or some abstractions from that; commonly, for example, formant positions, some indications of phonetic features such as nasality, and whether the source of the sound is periodic or gaussian noise. Some synthesizers have a relatively small vocabulary of fundamental units; for example, the phonemes. Although notionally the forty or so phonemes of English are the fundamental units of pronunciation, the same strong co-articulatory effects that make speech recognition difficult make intelligible, natural sounding speech difficult. If one uses a small number of fundamental units such as phonemes, complex rules must be applied so that they may be appropriately modified depending upon context. Another common choice is to store all the major phonetic variants as fundamentals units. In this scheme, there are usually contextually defined variants of particular phonemes. A still larger set of fundamental building blocks is required in the diphone approach which stores transition between adjacent phonemes thus requiring only slightly less than forty times forty fundamentals units (Thomas, *et al.*, 1984). A somewhat similar approach is to use demi-syllables.

In addition to the requirements for a synthesizer to produce the right sequence of sound units, the English language is also subject to a large number of variations in fundamental frequency, amplitude, speaking rate, spectral tilt, and degree of articulateness depending upon meaning and intent. These variations are known collectively as prosody.

The state-of-the-art in speech synthesis is that on a word by word basis, common words of English are generally pronounced fairly intelligibly. Very similar sounds such as "T", "K", "P", are more frequently confused than they are in real speech. However, given some listening experience with a high quality synthesizer and the context provided by narrative text, synthetic speech is intelligible enough so that most listeners can answer comprehension questions after listening to synthetic speech as well as after listening to real speech (Pisoni, 1982). Speech synthesizers today, however, do not sound natural and they make many errors when it comes to prosody, the pronunciation of proper

names, and non-homophonic homomorphs. Thus, whether or not today's speech synthesis systems are "good enough" for an application depends upon the application. Even subtle task variations within what is labelled as an application may provide quite different acceptability ratings. For example, one application of interest to phone companies is automated customer name and address (ACNA). In this application, a user specifies a phone number and receives name and address information, i.e., a reverse directory. In some cases, users wish to verify credit information and may have, for instance, a check with the customer's name and address written on it. In such cases, today's synthesizers, provided one obtains one of the highest quality, are sufficient. In other cases, however, sales people may be trying to map out a territory and need to find the customer's name and address "cold." For this purpose, today's commercially available synthesizers are probably not sufficiently accurate.

Guidelines for Using Speech Synthesis

There are several types of applications where speech synthesis provides a reasonable medium for computer output to a person. Speech output provides a way of understanding textual material when that is not possible by sight. It is an alternative for blind people, children too young to read, and the over one billion illiterate people in the world. The only real alternative in such cases is live or recorded human voice. For many applications this is prohibitively expensive. Speech synthesis is particularly appropriate when the materials must be flexibly presented or the textual basis changes frequently.

Speech synthesis is also particularly useful when eyes and hands are busy. Thus, for instance, it is both more efficient and safer for a machine tool operator to listen to instructions while focusing their visual system on the task at hand. A related useful aspect of speech as an output medium is its omnidirectionality. In a sense, it serves as its own orienting signal. So for instance, on a large factory floor, a combination of alarms with a central visual monitoring station can be replaced with verbal warnings. This means that someone may now hear the warning and go directly to the area where their involvement is needed rather than having first to go to the visual monitoring station. Similarly, if someone is making an adjustment in an awkward position inside a partially completed piece of machinery, that person can get feedback about the adjustment without moving out of position.

Speech, of course, also offers an alternative means of presenting information and as such can be a useful adjunct in educational settings or situations where the human operator is already overloaded. According to Wickens (1984), our ability to deal with a visually presented spatial task, and listening and com-

prehending verbal materials, is much more independent than trying to deal with two visually presented tasks, for instance. One can easily imagine the advantages of presenting problems requiring three dimensional visualization on a visual display unit while simultaneously giving auditory commentary. Research is underway to determine the most effective way of using auditory output in the information overload situation in which fighter pilots often find themselves.

Another aspect of speech synthesis which opens up a wide number of applications is the simple ubiquity of the telephone. The telephone offers a cheap, sturdy, potentially lightweight, and already deployed alternative to visual display units for the presentation of information. Unlike E-mail transmissions, the telephone offers point-to-point instant two-way connectivity. Thus, via a combination of using either touch-tone input or limited speech recognition and speech synthesis, one can gain access to data that is stored anywhere in the world from nearly anywhere in the world. Again, it should be noted that recorded human speech is an alternative in many of these situations but is generally prohibitively expensive. This is particularly true for information which changes rapidly; for instance, "news", or current weather and driving conditions. Tables 3 and 4 summarize some considerations for recorded speech vs. synthesis.

Recorded Speech vs. Synthesis

Even if one deploys speech synthesis in an appropriate situation, care must still be taken to insure that the technology is deployed appropriately within the application. It should be first noted that since intelligibility is not as high with speech synthesis as it is with human speech, it is useful to ensure that there is some redundancy in the messages. Telegraphic short cuts (which were

Table 3.—Guidelines for Use

- Totally recorded messages are
  —natural
  —intelligible
  —hard to edit
  —very hard to update
- Recombinant recorded messages are
  —almost natural
  —intelligible
  —limited in scope
- Synthesis (text-to-speech) is
  —flexible (prototype messages)
  —easy to edit
  —cheap to update
  —fairly intelligible
  —not natural
  —more attention demanding

Table 4.—Guidelines for Use

- Provide information in topic-comment order
- Provide high level maps of system
- Use medium length words
- Avoid words with multiple parts of speech ("run time buffer"?)
- Differentiate warnings, prompts, and feedbacks
- Adopt frequently used words
- Avoid negations
- Avoid long strings of nouns (also known as the "Long noun string confusion avoidance principle")
- Verb-object statements are easier than conditionals ("Enter first name" is better than "If first name, then enter")
- Use consistent command patterns (Forward/background", not "Next/back")
- Avoid ambiguous words ("Last" = "Final" or "Previous")
- Avoid "Telegraphese" (Memory cheap keep short unneeded)

originally designed in the 1950's to save the internal storage space of digital computers) have continued to be in vogue in instruction manuals and computer error messages in the much the same way that our appendix survives. Today, in our anatomy, it only provides grief and serves no useful function. In giving instructions to be followed, it is generally a good idea to repeat sections in this manner. "Proceed south on interstate 684 and take exit 8. Exit 8 will put you on Smith Road. You will take Smith Road, north-bound to the third light. At the third light you will turn right off of Smith Road onto . . . ." In addition, words should be chosen for messages which are fairly common words and yet not overly short. Short words tend to be more easily acoustically confused and are often ambiguous as well. Sentence structures should generally be active and fairly simple.

One of the things that is difficult about auditory interfaces is keeping track of the menu structures and where one "is" within that structure. To some degree these difficulties can be mitigated by using "maps" where some brief attention to visual stimuli is possible, by using distinctive voices at various levels or within groups in a mnemonic way, and by limiting menu choices to three or four at a time.

Many commercially available synthesis systems have a number of suitable parameters and defaults for those parameters. It is important *not* to assume that the default values are optimal for intelligibility. In many cases, *other* values of rate, fundamental frequency, and loudness may improve intelligibility. It may be worthwhile, if you are contemplating using a particular speech synthesis device, to do preliminary testing to determine a confusion matrix for the various phonemes. You may find particular confusions that you may want to avoid in your messages.

Listeners differ quite a bit in their ability to understand synthetic speech and this ability changes over time. This provides a challenge for the human factors professional since both within-subject and between-subjects designs

are problematic. It also implies that it is worthwhile to test out speech synthesis on populations that are truly representative of your users and to realize that there will be some learning involved. The positive side is that laboratory results may understate the performance that repeat listeners will eventually achieve in the field.

In speech synthesis applications, because listeners will improve over time, and there are large individual differences, it is probably highly desirable to allow user control of rate and to allow interruptions and replay. Adding a warning tone or beginning to a speech synthesis message, according to Simpson and Williams (1980), does not seem to help intelligibility. Since speech synthesis seems to require greater attentional demands than natural speech, this must be also taken into account.

Additional Speech Technologies

While speech synthesis and speech recognition are the two main voice technologies, there are also a number of others which have applications in human computer interactions. One such technology is language detection. In other words, the computer automatically determines which language is being spoken. This can be useful for directing users to the appropriate person or subsystem. It can also be used to scan large amounts of auditory data which would be of interest to a particular person.

Similar applications can be used for speaker identification. At this time, speaker identification only works within a fairly limited set of people. Speaker verification can be used in conjunction with speech recognition, but also in other applications as an added measure of security. Even the simple function of speech detection can be useful in certain contexts. For example, we could imagine a phone call that would be forwarded to a secretary if a conversation were taking place within an office. Similarly, we could alert potential visitors to the presence or absence of conversation in an office before they entered for a visit. We could also search phone lines sending data or voice, for the voice portions to be segregated and processed differently.

While analog techniques for storing and recording and playing human voice have existed for many decades, there are definitely advantages to storing, recording, and playing back human voice digitally. In some cases, it allows cheaper storage, i.e., less physical space. In addition, various error-correction and noise-elimination algorithms can be brought to bear more easily on digital speech. Digital speech may also be varied as to rate and fundamental frequency according to some schemes of digitization. Digitization also allows a number of security measures to be imposed through encoding-decoding schemes. Dig-

ital transmission saves bandwidth in much the same way that digital-speech storage saves space. Most of the comments in the section above on the presentation of speech synthesis apply equally well to the presentation of digitized human speech (but see Table 2).

Summary and Conclusions

Speech technology offers partial solutions for a number of application problems. The human factors professional should gain an understanding of the underlying technologies beyond what can be presented here. They should also familiarize themselves with the empirical work (see references). The main value, however, of such reading is to get a sense of what is possible and how to do your own evaluations. You cannot rely on any specific values for recognition accuracy or synthesis intelligibility. Your own users, tasks, and context will exert too big an influence on what will happen in your application.

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A Comparison of Early with Late Respondents to a Mailed Questionnaire

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ABSTRACT

Differences between early and late respondents to an opinion questionnaire survey, in which the total response was 98 percent of the universe, are analyzed. Those tending to respond early were those who were fellows of their Association, attended more meetings, knew more about their Association, felt that their Association's support of legislation was important, were better informed about their Association and were in accord with its policies.

The problem of non-respondents or late respondents is a vexing one for users of mail questionnaires. The literature contains many hypotheses about who does not answer questionnaires, whether there is a difference between respondents and non-respondents and if there is a difference, whether or not it influences the findings.

Concern about non-respondents has changed during the last 40 years from not being regarded as posing a threat to inferences from sample surveys, according to Frankel and Frankel,[1] to where it was considered so serious that the American Statistical Association had a National Science Foundation sponsored workshop on the non-response issue in 1973.

George Gallup also called attention to this research problem in his article "Opinion Polling in a Democracy".[2] The most significant work, however, was a three-volume report[3] published by a Panel on Incomplete Data established by the Committee on National Statistics of the Commission on Behavioral and Social Sciences and Education of the National Academy of Sciences. The primary focus in this report was on statistical means of controlling errors with some attention given to methods of increasing response to questionnaires and interviews.

Return rates for questionnaire studies vary from a low of about 5% for those conducted by survey firms doing studies of physician readership of medical journals to above 90% for some research by sociologists. From a sample of 1,769 teachers in 62 schools, 983 responded.[4] In a study of 850 cable television subscribers, 54% responded after three follow-up letters.[5] When part of the universe was given monetary rewards of 25 cents to $2 for returning the questionnaires, responses increased to 88% but those responding had lower incomes than the 54% in the first group not given money. A survey of 215 public administrators resulted in an 80.5% return.[6] A survey of 1,000 members of a professional executive woman's organization produced 545 returned forms.[7] The questions in these four surveys all seemed to be innocuous as were those utilized in comparing early with late respondents in the present study.

A compilation and evaluative analysis of the literature on factors affecting rates of returns of questionnaires was published in the *American Sociological Review*.[8] Response bias of respondents and non-respondents has been discussed by a number of survey specialists,[9–16] Question wording, sponsorship, readability, layout, and size in relation to rate of return are the subjects of other authors.[17–21]

Four factors are mentioned throughout the literature as affecting returns to mail questionnaires. They are: failures, involvement with and loyalty to the sponsor, interest in the topic, and education.

Failures are, in this context, those who have not done something considered "good" by the sponsors of the questionnaire. For example, unemployed alumni may consider themselves failures when surveyed by their colleges. That this type of individual responds later is shown in the studies by Shuttleworth[22] and Barnette.[23]

In another study,[24] teachers who did not have up-to-date instructional equipment in their classrooms tended not to respond to the complete questionnaire. They may have felt that they had "failed" to keep up with progressive teaching methods. Data relating to the failure factor, per se, were not obtained in the survey reported in this study.

Loyalty to the questionnaire sponsor, may be separated in this study, to only a small degree, from interest in the topic. That interest in the organization or institution is important in the early return of questionnaires is shown in studies by Phillips,[25] Franzen and Lazarsfeld,[26] and Britten and Britten.[27]

Method

To meet planning information needs of officers of the American Public Health Association, a questionnaire was sent to all APHA members in one state. Questions were designed to seek information such as whether or not

they knew the functions of the sections of their Association, qualifications for becoming a fellow, legislation the Association had supported, and research projects it was carrying out.

Other questions were included to determine if the respondents felt that membership dues they paid to APHA were justified, if they preferred a different method of voting for officers, if one profession should have more to say in the Association than others, and if they were satisfied with the section of which they were members.

The questionnaires were all mailed on the same day with a cover letter from the state health commissioner. A follow-up letter was sent to all non-respondents to the first mailing and a second one to those not responding to the second letter.

As the questionnaires were returned, each was stamped with the date received. A return of 98% of the universe was achieved, 216 out of 220. The "Post Card" technique was utilized to obtain the high return in this confidential survey.[28] This compares to the lower return rates of surveys cited earlier in which most questions solicited information on non-controversial issues.

Respondents were divided into these two groups, "early respondents", who answered previous to the first follow-up letter, and "late respondents" who returned their questionnaires after the first follow-up letter. There were so few who waited until after the second follow-up letter that they were combined with the late group. As shown in Table 1, there were 143 in the early group and 73 in the late group.

The objective of the analyses in this study was to determine whether those responding late to the questionnaire used are significantly different from those sending them back early. The data do not permit generalizations relating to questionnaire studies of other topics or of other populations.

In the analyses reported here four variables were selected: background data on respondents, their knowledge about activities and functions of the Association, their participation in the Association, and their degree of satisfaction with the Association's programs for members.

Table 1.—Early and Late Respondents Compared by Profession

	Profession											
	Physician		Nurse		San. Eng'r		Statis-tician		Health Educator		Others	
When Returned	N	%	N	%	N	%	N	%	N	%	N	%
Early	62	70	29	58	21	62	5	45	10	100	16	70
Late	26	30	21	42	13	38	6	55	0	0	7	30
Total	88	100	50	100	34	100	11	100	10	100	23	100

Table 2.—Early and Late Respondents Compared by Affiliation with the Association

	Affiliation					
	Fellow		Member		Other	
When Returned	N	%	N	%	N	%
Early	68	78	70	61	5	36
Late	19	22	45	39	9	64
Total	87	100	115	100	14	100

In relation to background, tabulations were made on their status in the APHA, that is whether they were a member or fellow, the section of the Association of which they were affiliated, and the specific profession of each respondent. Since office holding and chairmanships are confined to fellows, only a limited idea of participation of respondents could be obtained.

Differences between professions shown in Table 1 are not statistically significant at the conventional level ($p = .05$) by the Chi Square test even though a larger proportion of health educators and physicians than the other professions responded early.

Another variable that was examined was whether or not a respondent was a fellow. Fellows responded earlier as is indicated in Table 2. Although almost any member working in the health field who wants to apply can become a fellow, it is likely that those who decide to become fellows have greater interest in the Association. To become a fellow, however, would be attractive to those concerned about the activities of the Association, because only fellows are allowed to hold office and serve on committees. This identification with the objectives of the APHA might also account for the earlier responses of the fellows and be congruent with the conclusions reached by Sirles,[29] Clausen and Ford,[30] and Phillips.[25]

At first glance, data on attendance at annual meetings of the Association (Table 3) would seem to support the role of interest. Early respondents attended more meetings than the late respondents. By the Chi Square test, this was significant at the $p = .05$ level.

Table 3.—Early and Late Respondents Compared by Attendance at the Annual Meeting of their Association

	When Returned			
	Early		Late	
Number of Meetings Attended	N	%	N	%
None	15	10	17	23
One or More	128	90	56	77
Total	143	100	73	100

Table 4.—Members and Others of the Association and their Attendance at Annual Meetings

Number of Meetings Attended	When Returned: Early N	Early %	Late N	Late %
None	14	19	17	31
One or More	61	81	37	69
Total	75	100	54	100

When the factor of affiliation was taken into account though, the interpretation changed. Of all the fellows, only one had not attended any meetings; however, a tabulation (Table 4) of the members and others, in relation to their attendance at meetings, and whether they responded early or late, showed early respondents attended more meetings than the late ones.

Of interest was whether or not early respondents would be better informed about activities and functions of their Association than the late respondents. The APHA adopts positions on federal and state legislation, and supports federal programs of interest to its members.

In response to the question "Do you know whether or not the APHA actively supported or opposed any federal legislation this year?" a greater proportion of the late respondents did not know that their Association supported federal legislation (Table 5). When tested by the Chi Square test, this difference was found to be significant at the $p = .02$ level.

A similar relationship was found (Table 6) when they were asked: "What is your feeling about supporting federal agencies in such a way as to protect them from budgetary cuts and other abuses in any way possible?" A larger proportion of early respondents reported that this support of federal agencies was important to them while a higher proportion of the late ones said that they did not know about this function of their Association. The Chi Square test indicated that the probability of this happening by chance was low ($p = .02$).

Because the APHA carries on various studies, respondents were asked to

Table 5.—Respondent's Knowledge of Their Association's Support of Federal Legislation

Response	When Questionnaire Was Returned: Early N	Early %	Late N	Late %
Yes	40	28	9	12
No	11	8	6	8
Don't Know	92	64	58	80
Total	143	100	73	100

Table 6.—Attitude Toward Support of Relevant Federal Agencies

	When Returned			
	Early		Late	
Response	N	%	N	%
Important to Me	68	48	27	37
Not Important to Me	14	10	0	0
Don't Know	12	8	10	14
Didn't Know About This Function	49	34	36	49
Total	143	100	73	100

list one or two studies they knew about (Table 7). Sixty-six percent of the late respondents did not name any, while 53% of the early ones did list such research. This statistically significant difference ($p = <.05$) indicated that early respondents were better informed.

In an attempt to learn whether respondents knew the difference between members and fellows, they were asked this question: "Do you know the difference between a fellow and a member? If you do, what is it?" In Table 8 it is shown that early respondents were better able to do this than late ones ($p = .05$ with the Chi Square test). The three categories of "yes" answers have been ranked according to the correctness of the response. Therefore, "Yes I" includes those individuals giving the correct answer which is those who have responsible positions in the health field who wish to apply and are recommended by people who already are fellows. "Yes II" included those respondents leaving out either the recommendation requirement or that fellows needed to have a responsible role in public health, while included in "Yes III" are those stating that to become a fellow a member needed to be a public health worker.

These questions dealt with qualifications for being a fellow, and, in general, fellows replied earlier than others, so it was necessary to control the affiliation variable in Table 8. When this was done, the relationship was not significant. The difference was larger between the two groups. The fellows were, as was to be expected, better informed on this topic.

Finally, it was found that early respondents were more satisfied with their Society's policy of only fellows being allowed to hold offices and serve on

Table 7.—Whether or Not Respondents Listed Studies They Knew Their Association Had Conducted

	When Returned			
	Early		Late	
Response	N	%	N	%
Yes	76	53	25	34
No	67	47	48	66
Total	143	100	73	100

Table 8.—Knowledge of the Difference Between Fellows and Members

	When Returned			
	Early		Late	
Response	N	%	N	%
Yes I	24	17	3	4
Yes II	43	30	20	27
Yes III	57	40	32	44
No	19	13	18	25
Total	143	100	73	100

the Executive Council than those taking longer to return the questionnaires ($p = <.05$) (Table 9). Because this question dealt with the privileges of the fellows, and a greater proportion of fellows answered earlier than members, it was advisable to control again on the affiliation variable. When this was done, the difference between early response and high satisfaction with the Association disappeared. The fellows were satisfied and the members were dissatisfied.

Another question involved physicians working in public health who were members and fellows of the APHA. The question was: "Should physicians have more power than members of other professions?" Analysis showed that physicians felt that they should have that power while the other respondents did not ($p = <.05$).

Conclusions

Data from this questionnaire survey provided a unique opportunity to evaluate demographic bias in research with these instruments, especially because its completion rate was 98%. The tabulations presented herein show that misleading conclusions would result from data furnished by respondents to questionnaire surveys to which a significant proportion did not respond.

In this study interest in the survey sponsor and the topic of the questionnaire seemed to elicit an early response to it. The members of the Association who responded early had attended more meetings and were better informed about functions and activities of their Association.

Table 9.—Attitude Toward Only Fellows Holding Office and Being on The Executive Council

	When Returned			
	Early		Late	
Response	N	%	N	%
Yes	91	64	25	34
No	49	34	35	48
Other	3	2	13	18
Total	143	100	73	100

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The Washington Academy of Sciences Awards Program for Scientific Achievement in 1990

C. R. Creveling

National Institute of Diabetes, Digestive, and Kidney Diseases
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One of the many ways by which The Washington Academy of Sciences contributes to the growth and recognition of scientists in the Washington area is through the awards program of the Academy. Each year the Academy recognizes scientists who work in the Washington, DC area for scientific work of merit and distinction. Awards are made for outstanding contributions in Mathematics and Computer Sciences, Behavioral and Social Sciences, Engineering Sciences, Biological Sciences and Physical Sciences. In addition the Academy makes an award designated the "Distinguished Career in Science Award" to recognize persons who have made distinguished and overall contributions to science.

In keeping with the goals of the Academy which include the promotion of excellence in the teaching of science the Academy also presents awards for the Teaching of Science. These awards include the **Leo Schubert Award** for excellence in college teaching and the **Bernice Lambertson Award** for excellence in high school teaching.

The awardees are selected from those persons nominated by either Academy members or the public, by panels of experts in each of the respective fields. The decisions of the Award Committee are then considered by the Board of the Academy for final approval.

In 1990, the Awards were presented at a ceremony, held at the *Georgetown University Conference Center,* on *Friday, May 25th.* Following dinner, the program was opened by the President of the Academy, Robert M. McCracken.

After the award was presented, each person selected made a brief presentation on their work. The awardees were:

Dr. Jesse Bernard	Behavioral and Social Sciences
Dr. Angela M. Gronenborn	Biological Sciences
Dr. G. Marius Clore	Biological Sciences
Dr. Michael R. Moldover	Physical Sciences
Dr. Guillermo C. Gaunaurd	Engineering Sciences
Mr. Alan O. Plait	Leo Schubert Award
Dr. James Edward Falk	Leo Schubert Award
Mr. William John Entley	Bernice Lambertson Award
Mr. Grover C. Sherlin	Special Recognition for Services to the Washington Academy of Sciences

Behavioral and Social Sciences

The award in the Behavioral and Social Sciences was granted to DR. JESSIE BERNARD "For her ground-breaking work on the changing role of women—for making the invisible visible." Dr. Bernard has carved out for special study the "world of women." Beginning in 1925 she has worked in this relatively uncharted terrain of scientific research. The titles of her major books illustrate the range of her contributions: *Academic Women, The Future of Marriage, The Sex Game, The Future of Motherhood, Self-Portrait of a Family.* Her works have challenged most conventional thinking about women. Drawing upon her own prodigious store of learning, she has traced the changing role and status of women in modern history. Her explorations have probed the changing networks of women by social class, ethnicity, age, power, kin relationships, and friendships. In addition to using the traditional methodologies of social scientific research, she has uniquely drawn upon qualitative and largely fugitive materials: letters, diaries, photographs, arts, and crafts. In doing so she has opened new paradigms for research. She has brought the insights and understandings of basic science to the controversies surrounding social issues and problems. Her scholarship has profoundly influenced the work of modern sociology and of the surrounding disciplines. Dr. Jessie Bernard is not only one of the outstanding scholars of our times, she has also materially contributed to one of the major social changes in this period—the changing place of women in society. Dr. Bernard was nominated by Matilda White Riley.

Biological Sciences

The award in the Biological Sciences was conferred on the husband and wife team of Drs. ANGELA M. GRONENBORN and G. MARIUS CLORE for their contributions to the development and application of nuclear magnetic resonance spectroscopy and computer modeling for the determination of the three-dimensional structure of proteins in solution. Drs. Gronenborn and Clore have jointly developed an internationally renowned research program for the determination of three-dimensional structure of proteins and other macromolecules in solution. Their innovative research employs an integrated combination of nuclear magnetic resonance spectroscopy (NMR) and sophisticated computer modeling. This method harnesses the power of high magnetic field NMR spectrometers and modern computers to examine a very large number of three-dimensional conformations of the thousands of atoms that comprise proteins and selects those with favorable low-energy structures. This information coupled with the ranges of hundreds of interatomic distances derived from two dimensional NMR permits the determination of proteins, in aqueous solution, with a precision comparable with that of classical x-ray crystallography. At present the team of Gronenborn and Clore has produced 40 percent of the known protein structures by this technique. Drs. Gronenborn and Clore not only have made effective use of methods pioneered by others but have made unique and innovative contributions to this field. These awardees were nominated by Dr. Edwin D. Becker.

Physical Sciences

The award in the Physical Sciences was accorded to DR. MICHAEL R. MOLDOVER for outstanding achievements in the measurement of the thermophysical properties of fluids. In particular, for developing and using spherical acoustic resonators to redetermine the universal gas constant R, for accurately measuring the exponents and amplitudes characterizing phenomena near the critical points of fluids, and for demonstrating the ubiquitous nature of wetting layers and wetting transitions. Dr. Moldover has made outstanding contributions in many areas of the physical sciences, including critical phenomena, fluid interfacial phenomena, and acoustic metrology. He has performed theoretical work, although he is known best for his outstanding and creative experimental work. His contributions include models for the thermodynamic and interfacial properties of fluids and fluid mixtures, and more recently his work on the characterization of alternatives to the chlorofluorocarbon compounds believed to be depleting the Earth's ozone layer. Dr. Moldover was nominated by Dr. Victor Nedzelnitsky.

Engineering Sciences

The award in the Engineering Sciences was granted to DR. GUILLERMO C. GAUNAURD for his outstanding contributions in inverse scattering, particularly in acoustic resonance scattering. For over twenty years, Dr.Gaunaurd has been engaged in individual research on the interaction of acoustic, elastic and electromagnetic waves with material media. This effort has led to a basic understanding of the *scattering* processes occurring when waveforms emerging from projectors such as sonars or radars are incident on and reflected by penetrable targets, and of the waveforms *radiated* by bodies when they are excited into oscillation by various external agents. In brief, these have been twenty years devoted to the study of the radiation and scattering of mechanical and electromagnetic waves. Dr. Gaunaurd was nominated by Dr. Albert G. Gluckman.

Leo Schubert Award For Teaching of Science in College

The Leo Schubert Award for the Teaching of Science in College was presented to two persons. An award was made to Mr. Alan O. Plait for his excellence and innovative methods in the teaching of mathematics. Mr. Plait has had a long and distinguished career in the teaching of science and, particularly, in mathematics. He has developed and instructed a wide range of topics in such areas as electronics, mechanical engineering, reliability engineering, and quality assurance and control. Since 1963 he has taught mathematics. He received the USDA Graduate School Faculty Excellence Award in 1986. Mr. Plait served as Chairman of the Mathematics and Statistics Advisory Board from 1987 to 1989. Under his leadership the school significantly broadened its offerings in mathematics and advanced statistics. Mr. Plait, by incorporating anecdotes on the history and development of calculus, reveals a rarely seen dimension of calculus to his students. Formulas and solutions take on reality with real people attempting to find the answer to real problems. Mr. Plait's dynamic ability in the teaching of mathematics has become legendary throughout the Graduate Program of the USDA. Mr. Plait was nominated by Drs. Philip Hudson and Ronald MacNab.

The Leo Schubert Award was also given to DR. JAMES EDWARD FALK for his dedicated and enthusiastic teaching of applied mathematics and operations research, and for his sympathetic and valuable counseling of college students. Dr. Falk is Professor of Operations Research in the Department of Operations Research of The George Washington University. One phrase that typified Dr. Falk is "clarity of exposition" which underlies his outstanding

abilities as a teacher. He is able to present areas of applied mathematics so coherently and lucidly that students are drawn to the beauty of mathematics and to the value of its application. Dr. Falk's deep interest in and commitment to his subjects, both mathematical and human, are manifest in the excellence of his teaching. Because of his empathy with students at all levels, Dr. Falk is a much sought after counselor with respect to academic programs, research, and professional concerns. Dr. Falk was nominated by Dr. Richard M. Soland.

Bernice Lambertson Award For Teaching of Science in High School

The Bernice Lambertson Award for the Teaching of Science in High School was granted to MR. WILLIAM JOHN ENTLEY for his devotion to the teaching profession and endless energy directed toward the preparation of students for higher education and the real world. After twenty years as a physicist and engineer, Mr. Entley entered the teaching profession as a high-school physics teacher. Mr.Entley has promoted a thorough understanding of physics and stressed the relationship of physics and the other sciences to everyday life. In his teaching, Mr. Entley emphasizes practicality and logical objective thinking, the need for intellectual honesty, and the necessity to write and communicate effectively. He has devoted much of his own time after hours, on weekends, and during the summer months to extracurricular activities that involve students in dynamic experiences in the mixed disciplines of present-day science. Mr. Entley was nominated by Maynard J. Pro.

Special Award For Services to the Washington Academy of Sciences

The awards ceremony ended with the granting of a Special Award of Recognition to Mr. GROVER C. SHERLIN for his many years of devoted service to the Washington Academy of Sciences. Mr. Sherlin, in many cases single-handledly, maintained the records, mailing lists, the library of the Journal of the Washington Academy of Sciences, and the multitude of administrative details that provide the life blood of the organization.

The Academy thanks the Chairpersons of each of the selection committees for their diligent efforts in the selection of outstanding candidates in 1990.

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President's Report to the Membership for the year 1989–90

Robert H. McCracken

Bethesda, MD

Thanks to a group of dedicated, supportive, and active individuals, the Academy program from June 1989 through May 1990 was unusually useful. While it was necessary to make adjustments, solve some problems, and cope with some obstacles, administrative emphasis was placed upon the useful, external, charter functions of the Academy.

There was a pressing need to bring expenses within income. This was accomplished by steps which simultaneously increased the usefulness of the Academy.

With the help of a select group of fine people, costs were brought well under control, and a program of activities and lectures was developed which was highly useful to the educational system, the scientific community, and the public.

An objective of this administration, in promotion of science education, was to foster rapport with the University of the District of Columbia and both the scientific community and the local neighborhood. To this end, and to reduce high costs and eliminate severe parking problems, we moved the Academy's scientific and board meetings to the University of DC, where both a Metrorail station and a parking garage are available within a few feet, and the Academy is not charged for meeting space. (The official headquarters remain, at least until 1992, at 1101 N. Highland Street, Arlington, VA 22201.)

Speakers and their guests were hosted at dinner in a nearby restaurant. As in the past, a reception preceded each scientific colloquium, but now with volunteers, chiefly Edith Corliss, expertly providing a buffet of delightful variety, at only a small cost. The substantial saving (several hundred dollars per meeting) made possible another objective: to admit students and faculty

at no cost, and others for a very nominal charge. The much lower cost, far greater convenience, and current relevance encouraged attendance.

Many scientists and others who attended Academy functions at the University for the first time expressed very favorable impressions.

Another cost-cutting measure improved efficiency and accuracy by having the Journal sent to Academy Headquarters where it was mailed at a $100 saving by volunteers.

Another objective was to employ the monthly scientific colloquia as a forum for useful, cross-discipline dissemination of the status, problems, and progress of leading work in the respective fields.

Program Chair William Busch, of NOAA, brought eminent scientists to our scientific programs, usually co-sponsored by Academy affiliates, to disseminate the current status of relevant work at the horizons of their fields.

One of the most valuable functions of the Academy, the Washington Junior Academy of Sciences continued its excellent contributions to the development of tomorrow's leadership under the uniquely skillful guidance of Marylin Krupsaw, who was authorized to extend her fine work to the intermediate school level.

Another continuing, very important function for education, to which we also made some valuable new appointments, is the Joint Board on Science and Engineering Education. The JBSEE is sponsored by the Academy and the District of Columbia Council of Engineering and Architectural Societies; under the dedicated leadership of Dr. Donald Roe, it provides resource people and contact representatives for all the public, private, and parochial schools in the metropolitan DC area.

Competent, effective, inspired volunteerism is the life blood of non-profit organizations. At the risk of inadvertently missing some, for which, if so, I apologize, I thank the following for their dedication and support:

Dr. Jean Boek, who so ably chaired the nominating committee and assisted with other details; Dr. Philip L. Brach, Dean of the College of Physical Sciences, Engineering, and Technology, for his kind hospitality in hosting the Academy programs at the University of DC; Dr. William S. Busch, Program Manager, NOAA Undersea Research, who, as program chairman provided a valuable, relevant series of colloquia; Edith Corliss, both for her function as Vice President for Affiliate Affairs and for providing the excellent reception buffets; Dr. Cyrus R. Creveling, who, as chairman of the awards committee, administered an impressive awards program; Norman Doctor, for his generous help with the membership data-base and related problems; Dr. Thomas W. Doeppner, both for his service on the bylaws committee and for helpful advice on other matters; Dr. Alphonse F. Forziati, for chairing the committee of

tellers; Dr. William R. Graver and Dr. J. Terrell Hoffeld, for their help with the bylaws; Mrs. Marylin Krupsaw, for her outstanding work with students, as Vice President of the Washington Junior Academy of Sciences; Dr. Stanley G. Leftwich, both for his fine work as chairman of the bylaws committee, and for dedicated support in other matters; Eric O. Nystrom, for his substantial contributions in providing audio-visual services for Academy affairs; Dr. Donald W. Roe, for his valuable work as chairman of the Joint Board on Science and Engineering Education; Grover C. Sherlin, Treasurer, for more dedicated service in many more areas than could be listed on this page; Dr. Simon W. Strauss, our Eminent Scholar in Residence, for his wise counsel, guidance, and help on many matters.

Grover Sherlin, upon his election as treasurer, acquired and expertly overcame some serious problems. An independent, outside auditor was engaged (donated, at no cost to the Academy) who initially found that without the data that Sherlin had no access to, it was impossible to submit an accurate audit. As information became available, Norman Doctor kindly volunteered his effective assistance in assembling data and establishing an improved computerized data-base.

Working diligently with records of past years, Mr. Sherlin, with the cooperation of the Internal Revenue Service, developed corrections of previous years' irregularities, which led to the refunding to the Academy, with interest, of several thousand dollars of previously imposed penalties.

Mr. Sherlin also helped with the mountainous task of reestablishing and updating our affiliate society relations. He was also faced with the necessity of reassembling a valid membership list from incomplete information.

Dr. Stanley Leftwich chaired a committee to correct several inconsistencies and errors in the bylaws and to add a needed provision regarding conflict of interest. The rewrite was passed by the Academy membership in an almost unanimous (approximately 97 percent) vote.

Very dependable, high-quality audio-visual services were regularly provided at no cost by Eric Nystrom, using overhead projector, slide projector, radio microphone, amplifier-speaker system, and recorder, lent by National Capital Astronomers. We opened our program series with a special, free, public event at the University of the DC, co-sponsored with National Capital Astronomers: A Voyager-Neptune Fly-by party for the public, students, and others, free of charge, all costs privately donated, at no cost to the Academy. A large microwave antenna was rented to receive the Voyager images from the NASA satellite, which were projected to the full screen in an auditorium. Enthusiastic participants saw the Voyager images of Neptune and Triton upon arrival of

the radio signals at the Earth. A continental breakfast (costs donated) was also provided at no cost to the guests of the Academy.

It was gratifying to see such public enthusiasm at three o'clock in the morning, and on until about 9:30 AM.

We thank Dr. Philip Brach, Dean of the College of Physical Sciences, Engineering, and Technology, for hosting the program, as well as other Academy programs, which we believe were, as intended, of mutual benefit to the University and the Academy, as well as to the public, in building good neighborhood relations. We also thank Radio Station WGMS for not only repeatedly announcing the program, but also for voluntarily emphasizing it by playing Gustav Hoslst's Suite, "The Planets" for us!

The September lecture, "Voyager—Neptune—Triton," by Dr. Michael Kaiser, NASA Goddard Space Flight Center, reviewed early scientific results of that mission. In October, we heard "New French Marine Technology Extends Horizons of Undersea Exploration," by Dr. Guy Imbert, Centre Nationale de la Researche Scientifique, Marseille. He described two remarkable current developments that substantially extend human diving depth and time limitations, using new mixtures of breathing gas and diving equipment. In November, "A Palladium Curtain Descends over Utah" discussion by Dr. Robert L. Park, Physics Department, University of Maryland, put the hot topic of "cold fusion" to rest, detailing the reasons. In his January 1990 presentation, "Quasars and Quakes," Dr. Thomas A. Clark, a radio astronomer with NASA Goddard Space Flight Center, described his work immediately following the Loma Prieta earthquake, and continuing. With an "inverted" extremely accurate astronomical star-position measuring technique, very long baseline interferometry, he used the farthest observable objects in the universe—quasars—to measure the motions and velocities of the Pacific and North American tectonic plates, to an accuracy of 1 cm. He described the work and gave results of these important, ongoing measurements at several sites in California, Alaska, Hawaii, Japan and elsewhere. In his February lecture, "Bright Light Eye Damage: Infrared, Ultraviolet, and Blue," David Sliney, an ophthalmic health physicist at Edgewood Arsenal, advised of current knowledge on the damage mechanisms of various wavelengths of light, including the dangerous visible blue. Wear your amber "blue blockers" when exposed to bright white or blue! In March, well-known meteorologist and Academy member, Glen Brier, NOAA and University of Colorado, reported his current discovery of "Significant Periodicities in El Nino," which have globel climatic implications. April brought Kurt Stehling, NOAA, with an assessment of the "Future Potential of Lighter-than-air Craft in Military and

Civilian Applications." An eminent scientist in this field, he was also the balloon pilot in the popular IMAX film. "To Fly."

In May, the annual Academy Awards dinner and ceremony were impressively arranged and conducted by Dr. Cyrus R. Creveling, Chair of the Awards Committee, at Georgetown University. For the list of awards and awardees, see Dr. Creveling's report elsewhere in this issue. I am privileged to add my hearty congratulations to the winners of these awards.

Other important contacts were made for the Academy for future development of the enormous potential of the more than a half hundred professional societies in DC. Long-range goals, too long for short tenure, but while it lasted, June 1989–May 1990 was a very good year. I sincerely thank you for your support.

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1990 Washington Academy of Sciences Membership Directory

M = Member; F = Fellow; LM = Life Member; LF = Life Fellow; EM = Emeritus Member; EF = Emeritus Fellow; NRF = Non-Resident Fellow.

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Corrigenda

Corrigenda should be noted within the article: Gluckman, A. G. (1990). The discovery of oscillatory current. *Journal of the Washington Academy of Science,* **80**(1), 16–25.

(a) pg. 21, Table III, line 1, change to . . .Henry's 1838 *Experimental* Results . . .

(b) p. 24, line 4, change to . . .translated from his 19th *century* latinic . . .

(c) p. 25, Reference 16, line 2, change to . . .ADDITION au *Mémoire* de M. Savary sur l'Aimanation" ["ADDITION to the Academy of Sciences in July of 1826].

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